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ARMY RESEARCH LABORATORY

# Electrothermal-Chemical Modeling
# Workshop, 12–13 May 1993—
# Volume I

Gloria P. Wren
William F. Oberle
CONTRIBUTING EDITORS

ARL-SR-10                                                      May 1994

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**NOTICES**

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Aberdeen Proving Ground, MD 21005-5066

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**13. ABSTRACT (Maximum 200 words)**

This compilation contains presentations presented at the Electrothermal-Chemical (ETC) Modeling Workshop held at the U.S. Army Research Laboratory, APG, MD in May 1993. Also included is a summary of ongoing modeling efforts and experimental data which could enhance ETC model development.

**14. SUBJECT TERMS**

electrothermal-chemical, workshops, interior ballistics, liquid gun propellants

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# INTRODUCTION

An Electrothermal-Chemical (ETC) Gun Modeling Workshop was held at the Weapons Technology Directorate (WTD), U.S. Army Research Laboratory (ARL)(formerly the Ballistic Research Laboratory (BRL)) on 12–13 May 1993. The workshop was specifically focused on technical aspects of ETC gun modeling and was sponsored by the WTD/ARL. Thus, the meeting was not as broad in scope as an earlier meeting held at BRL under the sponsorship of the JANNAF Combustion Subcommittee on 9–11 July 1991.

The objectives of the workshop were to: (a) assess the current state of ETC modeling; (b) determine the class of problems currently being addressed by various organizations; (c) encourage exchange of ideas and modeling techniques among participants; and (d) provide recommendations for future work, particularly in view of declining research funds.

The following compilation contains: (1) the meeting agenda; (2) a list of current known U.S. ETC modeling activities; (3) diagnostics measurements desired by ETC modelers as summarized by the group; (4) presentations by organizations attending the workshop; and (5) a list of participants. The workshop benefitted greatly from the participation of university, industry, and government (Army, DNA, Navy) personnel and contractors who all worked toward the common goal of understanding ETC processes through modeling.

We would like to thank Ms. Sharon Richardson for her excellent administering of the workshop; each participant for their active roles during the workshop; each author and funding agency for allowing work to be reprinted in this compilation (note that there are unclassified/unlimited and unclassified/government & contractors only sections)—and Army, DNA and Navy personnel in many different agencies for their cooperation and support in this endeavor. The modeling community has made significant advances in understanding ETC gun interior ballistics over the past several years and continues to impact gun cartridge design. It is hoped that this compilation will convey the development of state-of-the-art models for ETC guns.

<div style="text-align:right">

Gloria Wren
Bill Oberle
Weapons Technology Directorate
Army Research Laboratory

</div>

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**Wednesday, May 12, 1993**

| | |
|---|---|
| 8:15 | Administrative Remarks<br>Sharon Richardson |
| 8:30 | Science Applications International Corporation, San Diego, CA<br>C.-C. Hsiao, Fred Su |
| 9:30 | General Dynamics Land System/GT-Devices<br>Niels Winsor |
| 10:30 | Break |
| 10:45 | Science Applications International Corporation, Ft. Washington, PA<br>Sandy Dash |
| 11:45 | Lunch |
| 1:00 | Sandia National Laboratories, Albuquerque, NM<br>Steve Kempka |
| 2:00 | FMC Corporation, Minneapolis, MN<br>Patrick Janke |
| 3:00 | Break |
| 3:15 | U.S. Army Armament Research, Development, and Engineering Center<br>Lee Harris |
| 4:15 | Pennsylvania State University<br>F. Cheung |
| 5:00 | Adjourn |
| 7:00 | No-host dinner at Tidewater Grille, Havre de Grace |

**Thursday, May 13**

| | |
|---|---|
| 8:30 | U.S. Army Research Laboratory<br>Gloria Wren |
| 9:00 | Olin Corporation<br>Hugh McElroy |
| 10:00 | California Research and Technology<br>Phil Hookham |
| 11:00 | Group discussion and wrap-up |
| 12:00 | Adjourn |

# Current ETC Modeling Activities in the U.S. (May 1993)

| Organization | Program Funding | Current Activities |
|---|---|---|
| 1. ARDEC | Army | 1. 0D* |
| 2. ARL | Army | 2. 1D Plasma, 0D, End - to - end ( Power Plasma, IB) |
| 3. Eli Freedman & Associate | Army | 3. Thermochemistry (BLAKE - ETC) |
| 4. FMC | IR & D, Services | 4. 0D*,1D,2D (Finite Difference),End-to-end,Inverse Ballistic Model |
| 5. GDLS | IR & D , Services | 5. 0D*, 1D*, 2D (Finite Element) |
| 6. LLNL | DNA | 6. 2D/3D, AMR code |
| 7. NC State University | Army, IR & D | 7. 1D Plasma |
| 8. Olin Corporation | IR & D | 8. 0D*, 1D*, 1 1/2 D* |
| 9. Paul Gough Associates | Army | 9. 0D, 1D |
| 10. Penn State University | IR & D, Army | 10. 2D (2 phase, multiple sites, detailed droplet shedding) |
| 11. SAIC, Atlanta | Army, DNA | 11. 1D Plasma, 0D*, End - to - end |
| 12. SAIC, Ft. Washington | Army | 12. 2D /3D (Upwind/Implicit) |
| 13. SAIC, San Diego | DNA | 13. 0D*, 2D (FCT), 3D potential |
| 14. S-Cubed, Maxwell Labs | DNA | 14. 0D/1D |
| 15. Sandia National Labs | Army, DoD/DOE MOU | 15. 2D Plasma |
| 16. CRT | DNA | 16. 2D (TVD-Adaptive Grid), 3D potential |

Note:  * ARL model extension

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# Diagnostic Measurements Desired by ETC Modelers

| Measurement | Status | Organization Addressing |
|---|---|---|
| *1. Degree of burning rate augmentation of SP by plasma or intense radiation source in local contact with plasma | 1. Now doing; With solid propellant and with proposed alternate ETC propellants | 1. ARL, Penn State, NC State |
| *2. SP burning rate law with plasma compared to conventional for bulk propellant | 2. Some data is available | 2. ARL, FMC |
| *3. Effects of plasmas on burning rate of liquids, gels & solids | 3. Need data, will soon be doing | 3. ARL, ARDEC |
| *4. Burning rate and/or mass generation effects in two - component systems for slurries (mixtures of liquid and solid propellant) | 4. Need data; efforts starting at ARL & ongoing at Penn State | 4. ARL, Penn State, FMC |
| 5. Location of reaction front in bulk homogeneous energetic liquid vs. two phase | 5. Important; no ongoing efforts directly addressing issue, but feasibility is an issue | 5. N/A |
| 6. Effects of changes in plasma mass on mixing (Thermal energy vs. momentum) | 6. SNLA experiments have not yet shown a significant influence | 6. SNLA |
| 7. Analysis of closed bomb experimental data via fluid dynamic models | 7. Can be done (GTD) | 7. ARL will share closed bomb data with GTD |

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# Diagnostic Measurements Desired by ETC Modelers

| Measurement | Status | Organization Addressing |
|---|---|---|
| 8. Rates of droplet formation in liquid propellant ETC designs | 8. Penn State can perform diagnostics | 8. None |
| 9. Plasma pressure, exit velocity, ablation rates, species composition, temperature | 9. Pressure, temperature and ablation rates have been measured in some low power diagnostic fixtures. Other measurements extremely difficult. | 9. SNLA, ARL, NC State |
| 10. "Benchmarch experiments" for community model validation | 10. Needed, but time consuming. Experimentalists could all supply carefully obtained data sets for model validations. | 10. Groundrules need to be worked out for study |

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ARL WORKSHOP ON ETC MODELING

# RESULTS, METHODS AND PLANS FOR 0, 1 AND 2-DIMENSIONAL ETC MODELING AT GT-DEVICES

## Niels Winsor, Bob Greig

## Jon Earnhart and Dave Hurlburt

## 12-13 MAY 1993

# MANY THANKS!

The assistance of many Government, Olin and other personnel is gratefully acknowledged. In particular, Ron Anderson, Joe Buzzett, Paul Gough, Arpad Juhasz, George Keller, Ed Lilliott, Hugh McElroy, Dennis Worthington and Gloria Wren contributed either directly or by helping with codes or documentation.

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# ETC MODELING WORK

- IBHVG2 ENHANCEMENTS & DOC

- XNOVAKTC COMPUTATIONS

- FETC EXPERIMENTS

- FUTURE SIMULATION PLANS

# IBHVG2 UPDATES

- ETC ENHANCEMENTS

- ETC TUTORIAL

- GENERAL DOCUMENTATION

- COORDINATION WITH OLIN

# ETC ENHANCEMENTS

- ELECTRIC POWER INPUT

- ENERGY EQUATION MODS

- BURN RATE CONTROL

- ETC OUTPUT DATA

# 30mm OLIN EXP. DATA vs. CODE RESULTS
## OC26    PC1



PRESSURE (kpsi)

TIME (ms)

□ IBHVG2        —— EXP

GT-Devices
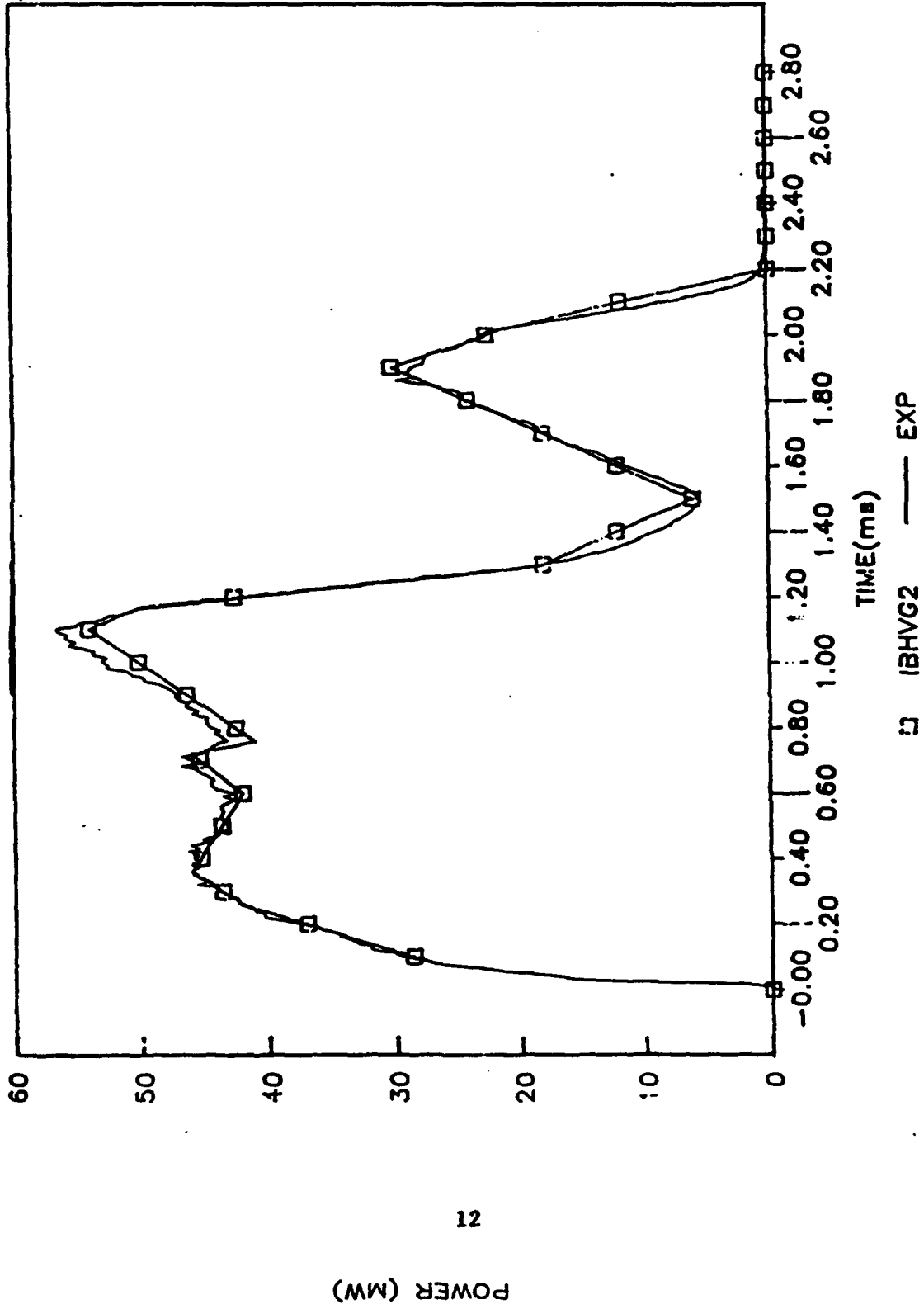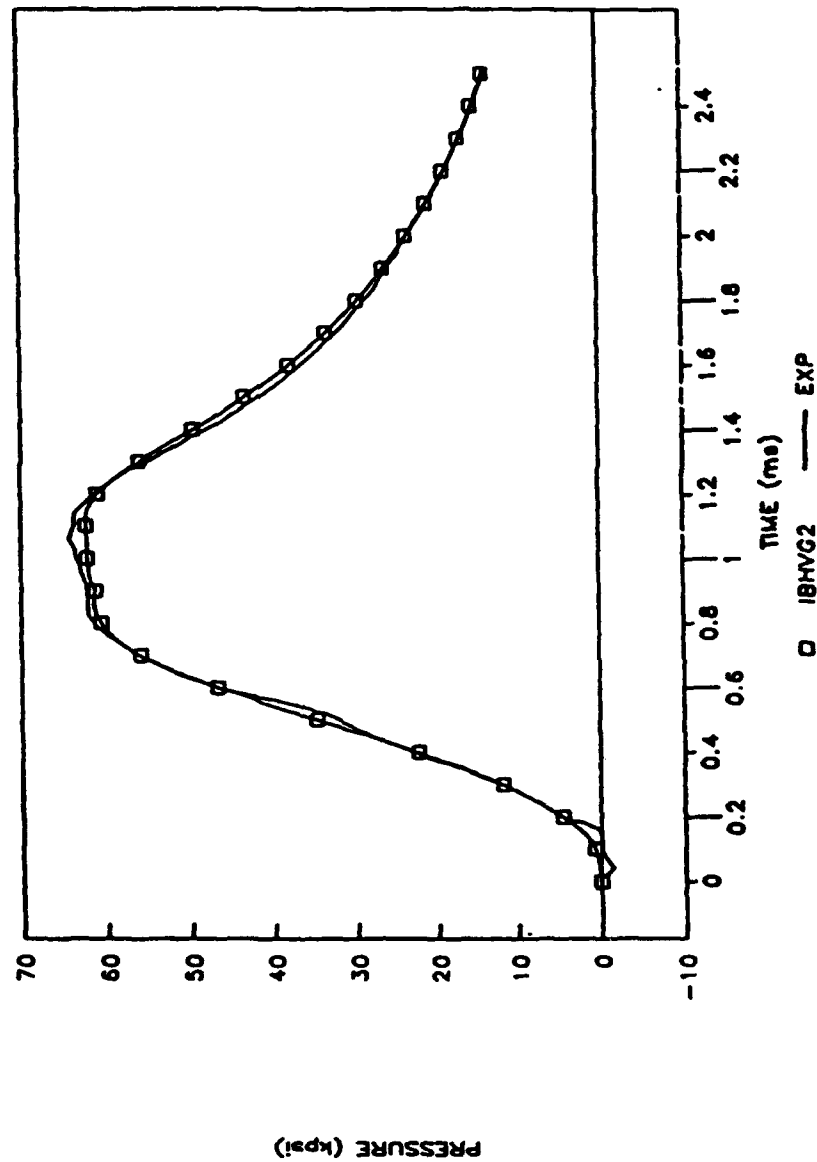
## CODE AND EXP. PROJECTILE TRAVEL
### OC26
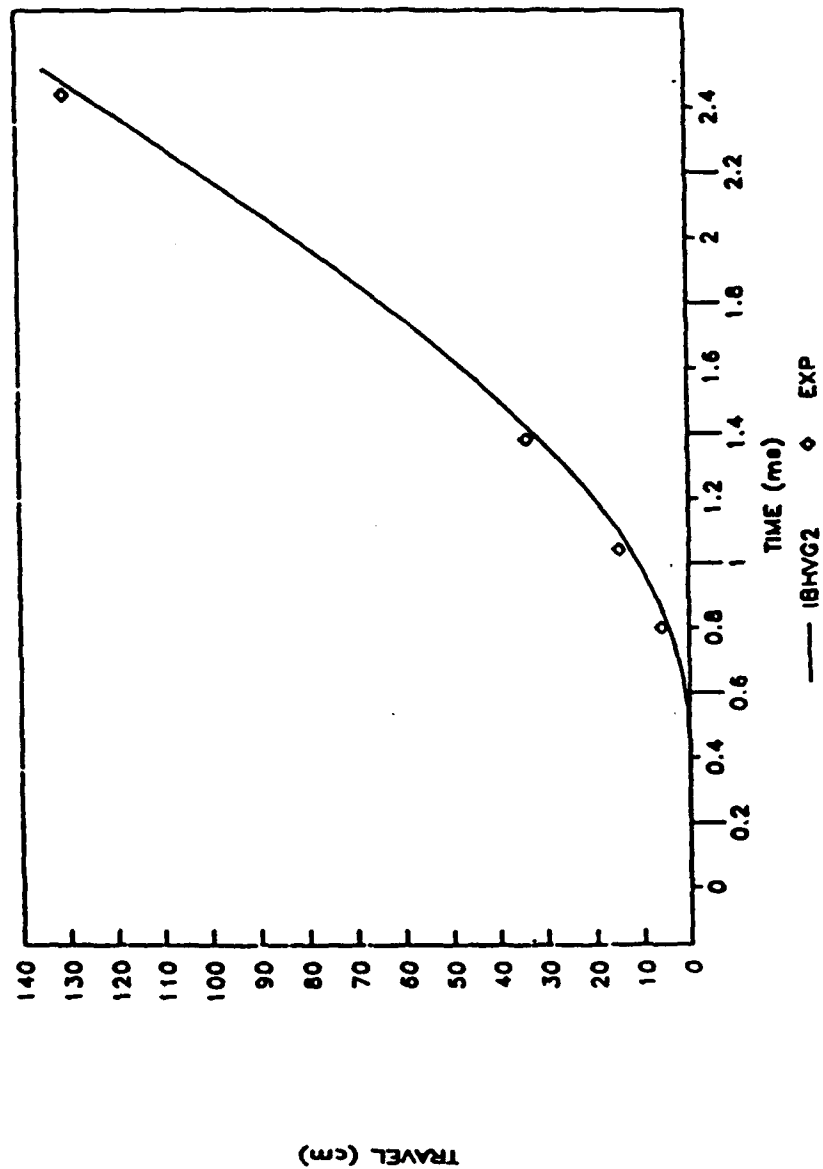
# ETC TUTORIAL

- FEB 92 DRAFT TR-2829 + TUTOR

- MAR 93 REISSUE -> PICATINNY

- TUTORIAL IN PROCESS AT ARL

# XNOVAKTC TRIALS

- AXIAL WAVE EXPERIMENTS

- POSTPROCESSOR CHANGES

- PROPELLANT ISSUES

- DOCUMENTATION STATUS

# AXIAL WAVES

- EXPERIMENTAL GEOMETRY

- BREECH IGNITION

- XNOVAKTC APPROXIMATIONS

- COMPARISON WITH EXPERIMENT

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## LOADING GEOMETRY

OC26



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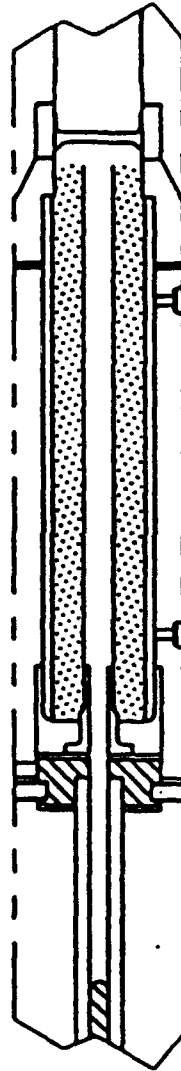
# EARLY BREECH IGNITION CAUSES AXIAL WAVE



EXPERIMENT WITH AXIAL WAVE
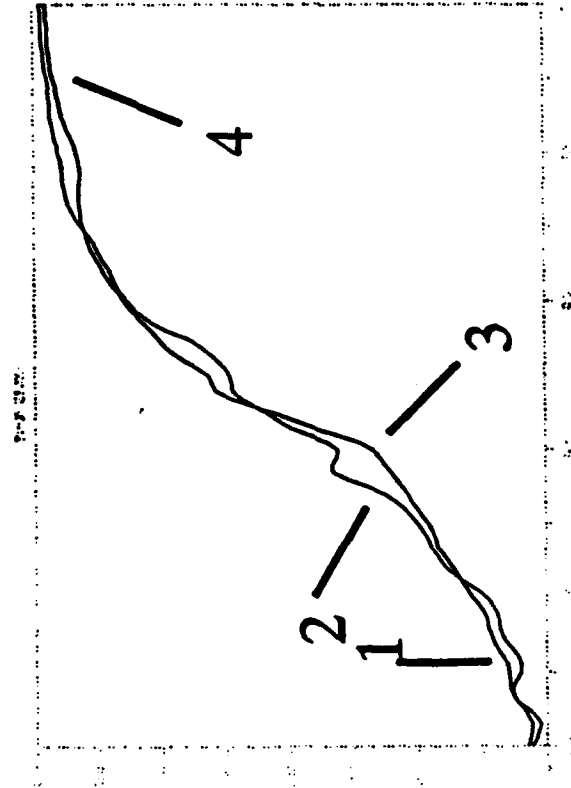
SIMULATION OF AXIAL WAVE
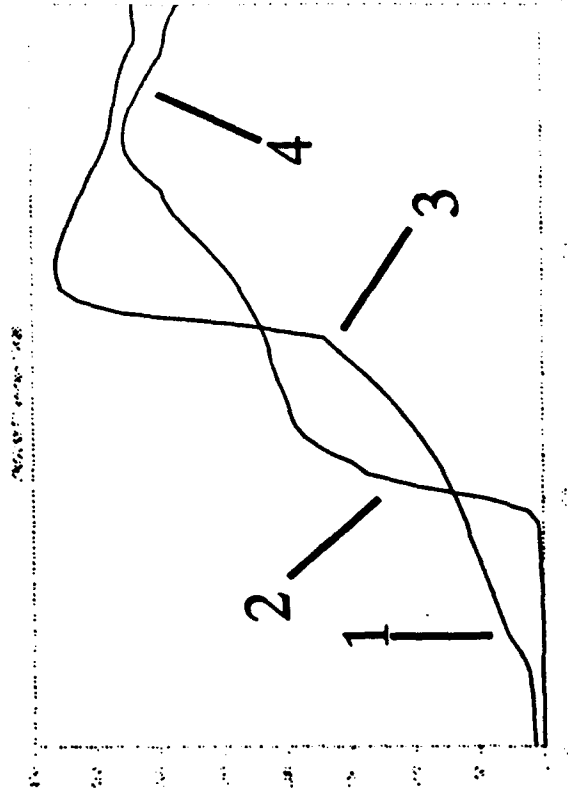
**EXPERIMENT**

1. Breech overpressure

2. Shock reaches front

3. Reflection reaches breech

4. Waves decay

**COMPUTATION**

A. Breech ignition drives waves.

B. Wave steepens to shock during bed transit.

C. Wave decays after 2 transits.

# FETC EXPERIMENTS

- MODEL EXTENSIONS

- PLASMA CHANNEL STABILITY

- CHANNEL WALL STRENGTH

- BASIC BALLISTIC LAUNCH

GT - Devices

# FETC EXTENSIONS

- LONG, THIN FINITE ELEMENTS

- RIGID, FRANGIBLE MEMBRANES

- MORE COMPLETE CHEMISTRY

- IGNITION MODELS

# PLASMA CHANNEL

- **MULTIFLUID TRANSPORT**

- **FCT BOUNDARY MAINTENANCE**

- **DISSIMILAR SOUND SPEEDS**

- **PHYSICAL IMPLICATIONS**

88, 99, ZZ = -2.00+01 -1.00+01 -5.00+01   DENSITY

88, 99, ZZ = -2.00+01 -1.00+01 -5.00+01   PRESSURE

current values are set by
maximum value      : 1.00+01
minimum value      : 3.00+01
contour interval   : 4.55/1 -02
please input units a interval

please input an identifying name for the object
g6/d
you have so far input the following objects:
nr  1 name g6/
nr  2 name g6/d
and you have displayed in the last figure the following
1 objects

please input how many objects you would
like to see in the next figure, default=  1

please input the   1 desired object(s)
in the order you desire them to be drawn

# CHANNEL WALL

- FLUID-SOLID BOUNDARY

- DELTA-PRESSURE BREAKS

- CLOSED-BOMB TEST

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135

135    0.1996E+00 0.3221E+01
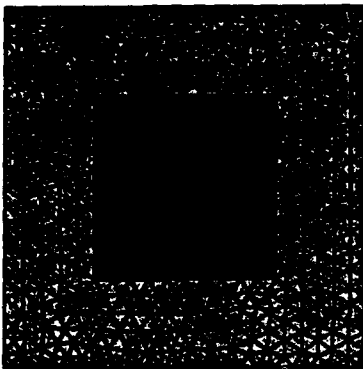
# BALLISTIC LAUNCH

- FULL 120 MM GUN TUBE

- ROD, SABOT, IGNITER

- IGNITION FLAMESPREAD

- PROJECTILE LAUNCH

GT - Devices

# FUTURE WORK

- 120 MM ETC ANALYSIS

- IBHVG2 POST-PROCESSING

- XKTC ETC INCORPORATION

- FETC CHEMISTRY MATCHING

# PRODUCTS MENTIONED

**IBHVG2, VERSION 5.04, WITH ETC EXTENSIONS**

**SEE GLORIA WREN FOR DETAILS OR COPIES**

**XNOVAKTC, VERSION 10426**

**SEE GEORGE KELLER FOR INFORMATION**

**CASEVision/Toolworks VERSION 1.1.1**

**SEE SILICON GRAPHICS UN-EXPRESS**

**1-800-800-7441  Cost $1500 for 1-user Indigo**

**FORTRAN LINT, Version 2.90**

**SEE IPT CORP, 1-800-944-5468, $3900 / 1-user**

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# MULTI-DIMENSIONAL SIMULATION OF LIQUID AND SOLID PROPELLANT ETC GUN INTERIOR BALLISTIC FLOWFIELDS

S. M. Dash, A. Hosangadi and N. Sinha

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Phone: 215/542-1200  Fax: 215/542-8567

## MAY 12 & 13, 1993

Presentation at:

ETC MODELING WORKSHOP
U.S. Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5066

# TOPICS

- **CRAFT FINITE-VOLUME UPWIND/IMPLICIT CODE**
  - Brief Overview of Numerics
  - Requirements for ETC Gun Simulation

- **BASIC CRAFT UPGRADES FOR ETC GUN SIMULATION**
  - Gridding: Dynamic/Blanking/Embedding
  - Thermochemistry: Liquid EOS/Virial EOS
  - Plasma Code Coupling/Quasi-Steady

- **PROGRESS TOWARDS DEVELOPMENT OF CRAFT/LP-ETC MODEL**
  - Gas/Liquid Equilibrated Formulation
  - Comparisons with Coffee LPG Code Predictions
  - Comparisons with FMC Shots
  - LES Turbulence Modeling/Subscale Terms

- **PROGRESS TOWARDS DEVELOPMENT OF CRAFT/SP-ETC MODEL**
  - Solid Propellant Burn Formulation and Integration into CRAFT
  - Comparisons with GDLS Shots

- **FUTURE DIRECTION/MULTI-PHASE FLOW UPGRADES**
  - Eulerian Solver/Volumetric Effects/Droplet Formation at G/L Interface — LP-ETC
  - Lagrangian Solver/Discrete Particle Combustion/Erosion of Particles from Surface — SP-ETC
  - Plasma Upgrades/Unsteady + Use of CRAFT Numerics

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# ETC MODELING PHILOSOPHY

- **USE OF ADVANCED STATE-OF-THE-ART NUMERICS AND RESOLVED GRIDS**

  - Minimize errors associated with numerical dissipation, etc. for adequate simulation of instabilities and turbulent/vortical structure

- **INCORPORATE WELL-ESTABLISHED MODELS AND DATA SETS FOR PROCESSES WELL UNDERSTOOD, e.g., BALL PROPELLANT COMBUSTION**

- **INCORPORATE SIMPLEST PLAUSIBLE MODELS FOR PROCESSES NOT WELL UNDERSTOOD, e.g., LIQUID/PLASMA INTERFACE**

- **PERFORM SENSITIVITY STUDIES TO UNDERSTAND INFLUENCE OF MODEL MODIFICATIONS/UPGRADES, e.g., SUBSCALE LES MODELS FOR LP/ETC**

- **SYSTEMATIC MODELING UPGRADES AS REQUIRED BASED ON SHOT DATA COMPARISONS**

  - Understanding processes emphasized

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# ETC GUN MODELING REQUIREMENTS

**THERMO**
- VIRIAL EOS
- LIQUID/SOLID EOS

**MULTI-PHASE**
- EQUILIBRATED MIXTURES
- G/P,D NONEQUILIBRIUM
  - EULERIAN
  - LAGRANGIAN
- DROPLET FORMATION/
  PARTICLE EROSION

## NUMERICAL FRAMEWORK
- CONSERVATIVE, HIGHER-ORDER, NON-DISSIPATIVE
  - INSTABILITIES
- STRONGLY-COUPLED/IMPLICIT TREATMENT OF NONEQUILIBRIUM SOURCE TERMS
- DYNAMIC GRIDDING, GENERALIZED BC

**PHYSICS**
- PLASMA COUPLING
- LES TURBULENCE
- PROJECTILE AERO

**CHEMISTRY**
- GAS-PHASE
- LIQUID/DROPLET
- SOLID/BED-PARTICLE

# CRAFT CODE FEATURES FOR PROPULSIVE FLOWFIELD SIMULATION

| | |
|---|---|
| *NUMERICS* | • 1D/2D/AXI/3D Finite-Volume Discretization |
| | • Implicit, Higher-Order Upwind (Roe/TVD) Formulation |
| | • Fully Implicit Source Terms/Boundary Conditions |
| *GRID FEATURES* | • Grid Dynamics to Account for Moving Boundaries |
| | • Grid Patching/Blanking for Complex Geometries |
| | • Solution-Adaptive Gridding |
| | • Hybrid Structured/Unstructured Formulation for Multi-Body Problems |
| *THERMOCHEMISTRY* | • Real Gas Mixtures (Calorically and Thermally Imperfect/JANNAF Thermo Tables/Virial EOS) |
| | • Finite-Rate Chemistry/Arbitrary Number of Species and Reactions |
| | • Fully Implicit Source Term Linearization |
| *MULTI-PHASE FLOW* | • Nonequilibrium Particle/Droplet Solvers (Eulerian and Lagrangian Formulations) |
| | • Gas/Liquid Equilibrium Formulation |
| | • Grain/Ablative Coupling Including Surface Recession and Interior Burning |
| *TURBULENCE* | • k-ε Formulation with Compressibility/Vortical Upgrades and Several Low Re Near-Wall Formulations |
| | • LES Subgrid Scale Models of Menon and Madabhushi |
| | • Particle Dispersion Formulations |
| *APPLICATIONS* | • Electrothermal Chemical (ETC) Gun |
| | • Regenerative Liquid Propellant Gun (RLPG) |
| | • Ram Accelerator |
| | • Solid /Liquid Propellant Rocket Motors/Exhausts |
| | • Ducted Rocket |
| | • Vertical Launcher Interactions |
| | • Turbulence/Multi-Phase Jet Research |

# CURRENT PROGRAMS UTILIZING CRAFT CODE

| SPONSOR | PROGRAM | CODE | APPLICATIONS/FEATURES |
|---|---|---|---|
| NASA/LaRC | Jet Research | CRAFT/JR | • Jet structure, steady & unsteady<br>• RS & LES turbulence models |
| MICOM | Tactical Missile Interactions | CRAFT/TM | • Missile propulsive/aero interactions<br>• Nonequilibrium metallic oxide particles (Al2O3,...) |
| ARL | ETC | CRAFT/LP-ETC | • Liquid propellant ETC - gas/liquid equilibrated mixture ---> droplet combustion |
| | | CRAFT/SP-ETC | • Solid propellant ETC - fixed bed combustion ---> fluidized bed/particle combustion |
| NSWC | VLS Interactions | CRAFT/TM | • Vertical launcher interactions including particle erosion/ablation<br>• Nonequilibrium particles |
| MICOM | Advanced Technology | CRAFT/* | • Multiple body problems<br>• Hybrid structured/unstructured solver |
| AFOSR | Ram Accelerator | CRAFT/RAM | • Ram accelerator simulation<br>• Turbulence/combustion research |
| MICOM | Ducted Rocket | CRAFT/DR | • Ducted rocket<br>• Carbon particulate combustion/dense loadings |
| ARL | LPG | CRAFT/LP | • Liquid propellant gun simulation<br>• Vortex shedding/LES research |

# OVERVIEW OF BASIC NUMERICS

- **FINITE-VOLUME DESCRETIZATION**

$$\frac{\partial}{\partial t}\iiint Q dV + \iint (E_{i+1/2} - E_{i-1/2}) d\eta d\zeta + \iint (F_{j+1/2} - F_{j-1/2}) d\xi d\zeta + \iint (G_{k+1/2} - G_{k-1/2}) d\xi d\eta$$

$$= \frac{1}{Re}\iint (R_{i+1/2} - R_{i-1/2}) d\eta d\zeta + \iint (S_{j+1/2} - S_{j-1/2}) d\xi d\zeta + \frac{1}{Re}\iint (T_{k+1/2} - T_{k-1/2}) d\xi d\eta + \iiint D dV$$

- **CONSERVATIVE/IMPLICIT METHODOLOGY REQUIRES TIME LINEARIZATION OF FLUX VECTORS E, F, etc. WITH REPEAT TO Q**

$$Q^{n+1} = Q^n + \Delta Q, \quad E^{n+1} = E^n + [A]\Delta Q, \quad F^{n+1} = F^n + [B]\Delta Q$$

$$Q = (\rho, \rho u, \rho v, \rho w, e, \alpha_1, \alpha_2, \ldots); \; n \text{ variables}$$

A, B, C, etc. — n x n block non-sparse matrices

  - **VISCOUS AND SOURCE TERMS ALSO LINEARIZED AND INTEGRATED IN A STRONGLY COUPLED FASHION**

**DISCRETIZED FORM IS:**

$$[I + \delta_\xi A - W][I - W]^{-1}[I - \delta_\eta B - W][I - W]^{-1}[I + \delta_\zeta C - W] = R.H.S.$$

- **FLUX EVALUATION** ($E_{i+1/2}$, $E_{i-1/2}$, etc.) **USING UPWIND Roe/TVD DIFFERENCING**

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# JACOBIAN OF THE FLUX VECTORS

$$\hat{A} = \begin{bmatrix} \cdots \end{bmatrix}$$

## NEED TO EVALUATE THE PRESSURE DERIVATIVES

$$\frac{\partial P}{\partial \rho} \; , \; \frac{\partial P}{\partial \rho U} \; , \; \cdots \; , \; \frac{\partial P}{\partial e} \; , \; \cdots \; , \; etc.$$

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# UPWIND NUMERICAL FLUX CALCULATION

- **NUMERICAL FLUX AT CELL INTERFACE IS EVALUATED IN AN UPWIND FASHION**

- **FLUX DIFFERENCES ARE BASED UPON THE SIGN OF THE EIGENVALUE**

- **FLUX AT THE CELL INTERFACE $E_{i+\frac{1}{2}}$ IS GIVEN BY**

$$E_{i+\frac{1}{2}} = \frac{1}{2}\left[E_i + E_{i+1} + E^-_{i+\frac{1}{2}} - E^+_{i+\frac{1}{2}}\right] + \text{higher order fluxes}$$

$E^-_{i+\frac{1}{2}}$ $=$ contribution of waves travelling in negative direction

$E^+_{i+\frac{1}{2}}$ $=$ contribution of waves travelling in positive direction

with

$$E^\pm_{j+\frac{1}{2}} = \frac{1}{2}\left[R_{j+\frac{1}{2}}(A \pm |A|)_{j+\frac{1}{2}} L_{j+\frac{1}{2}}\right](Q_{j+1} - Q_j)$$

**R and L are n x n block matrices containing the right and left eigenvectors, respectively.**

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# DYNAMIC GRID COMPUTATIONS

| | |
|---|---|
| **EQUATIONS** | $$\int_{t_2} Q dv - \int_{t_1} Q dv + \int_{t_1}^{t_2} \oint_{S(t)} \vec{n} \cdot \vec{F} \, ds dt = \int_{t_1}^{t_2} \int_{V(t)} \Phi dv dt$$ <br><br> Term I     Term II     Term III <br><br> Term I:    PRIMARY CONSERVED VARIABLES <br> Term II:   FLUX TERMS <br> Term III:   SOURCE TERMS <br> V(t):      TIME VARYING VOLUME |
| **METHODOLOGY** | • **TREAT GRID AS PURELY GEOMETRIC QUANTITY, i.e., DEFINITION OF CONTRAVARIANT VELOCITY UN-CHANGED** <br> • **EVALUATE FLUX TERM BY ASSUMING GRID IS HELD CONSTANT AT TIME-AVERAGED VALUE** <br> • **INCLUDE ADDITIONAL FLUX ARISING FROM CELL FACE MOTION** <br> • **EVALUATE SOURCE TERM FOR THE GRID AT THE NEW TIME LEVEL, THUS GIVING:** <br><br> $$\left( \frac{Q^{n+1} - Q^n}{\Delta t} \right) V^{n+1} + Q^n \left( \frac{V^{n+1} - V^n}{\Delta t} \right) + \overline{F}_n^{n+1} \overline{S} \Delta t = \Phi^{n+1} V^{n+1}$$ <br><br> $F_n = \vec{n} \vec{F}$, and $\overline{S}$ is the time averaged metric |
| **NUMERICS** | • **SPECIFY GRID MOVEMENT AS A FUNCTION OF TIME** <br> • **EVALUATE $F_n$ AS A THIRD-ORDER UPWIND BIASED FLUX** <br> • **SOLVE LINEARIZED IMPLICIT OPERATOR USING ADI PROCEDURE** <br> • **USE NEWTON ITERATION FOR HIGHER ORDER ACCU-RACY IN TIME** |

"INITIAL GRID IN GUN CHAMBER"
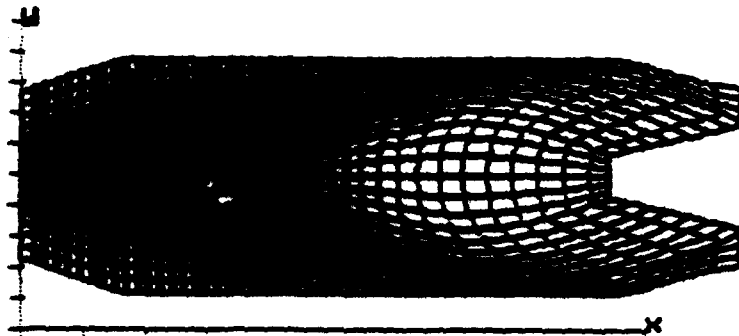
"GRID IN GUN CHAMBER AT 0.8 TS"
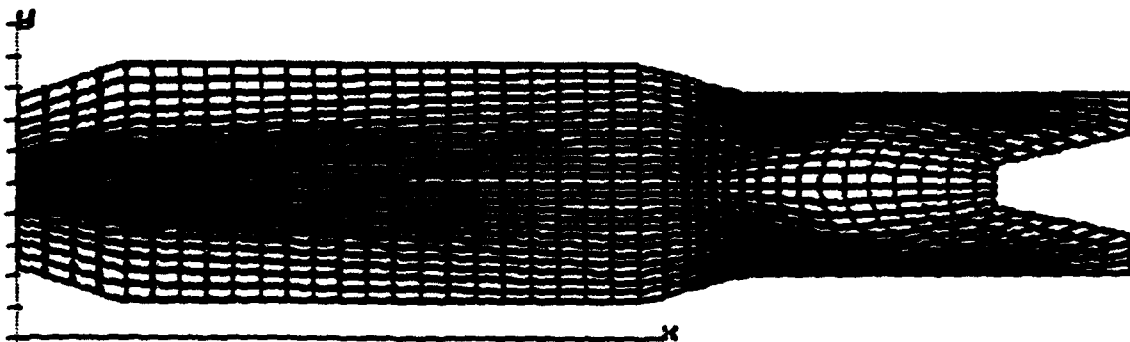
"LOG TEMPERATURE LEVELS AT 1.495 ms"

"5p ETC SHOT +5"
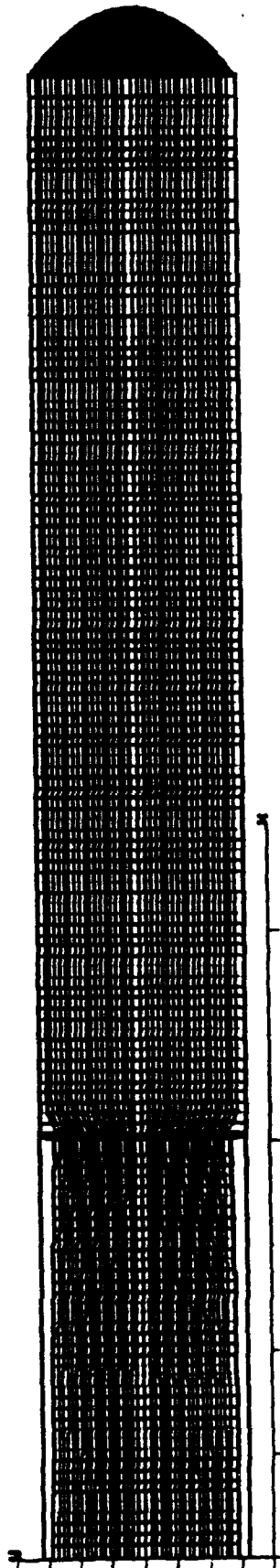
# PATCHED GRIDDING IN PARCH (FROM PARC)

- **SIMPLE GRIDS/COMPLEX GEOMETRY**
- **SINGLE DOMAIN/NO BLOCKING INEFFICIENCY**



PHYSICAL DOMAIN

COMPUTATIONAL DOMAIN
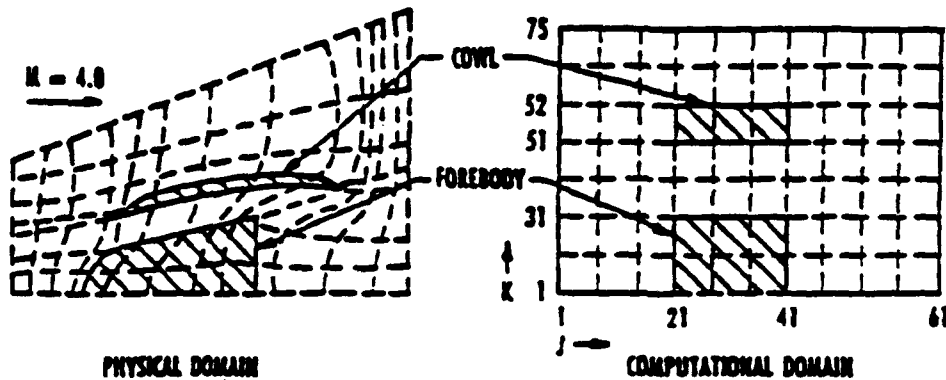
| J-Constant Index Class | | | | |
|---|---|---|---|---|
| Segment Number | J Index | K-Indices | | Sign of Normal |
| | | Min. | Max. | |
| 1 | 1 | 1 | 75 | 1 |
| 2 | 21 | 1 | 31 | -1 |
| 3 | 41 | 1 | 30 | 1 |
| 4 | 61 | 22 | 74 | -1 |

| K-Constant Index Class | | | | |
|---|---|---|---|---|
| Segment Number | K Index | J-Indices | | Sign of Normal |
| | | Min. | Max. | |
| 1 | 1 | 1 | 20 | 1 |
| 2 | 1 | 42 | 61 | 1 |
| 3 | 75 | 2 | 61 | -1 |
| 4 | 31 | 22 | 41 | 1 |
| 5 | 51 | 21 | 41 | -1 |
| 6 | 52 | 21 | 41 | 1 |
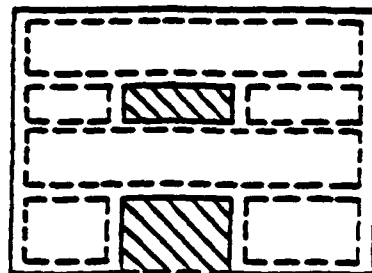


J-PATCHES

K-PATCHES

**GEOMETRY**

Subsonic Outflow

Subsonic Outflow

P = 1 atm
T = 300°K

Subsonic
Outflow

Subsonic
Outflow

P = 10 atm
T = 1500°K
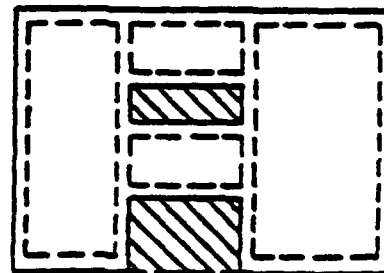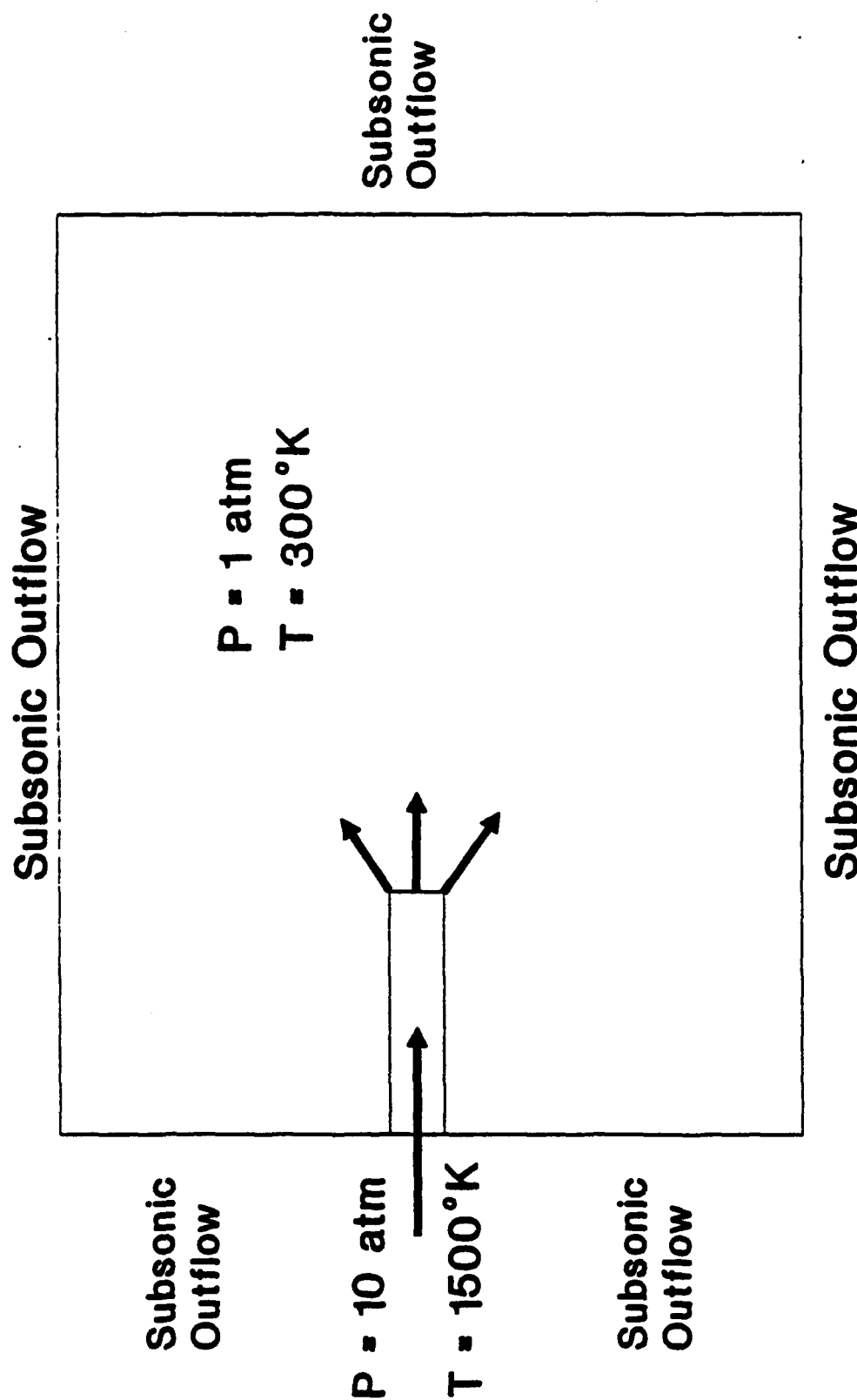
Figure 1. Schematic of Coupled Two-Dimensional Model Problem.
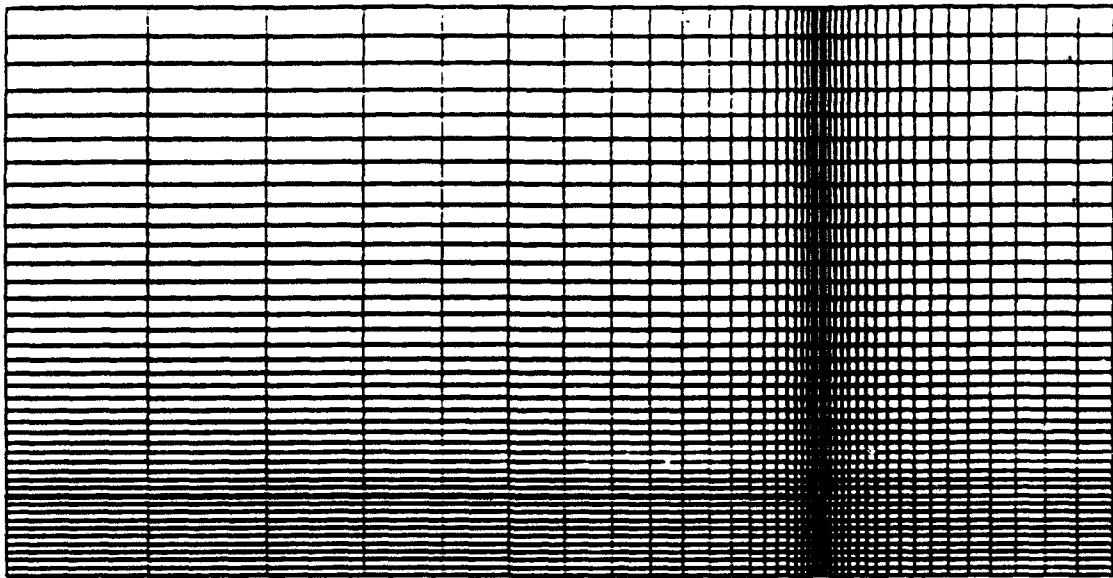
**Figure 2a.** Numerical Grid for Two-Dimensional Model Problem.
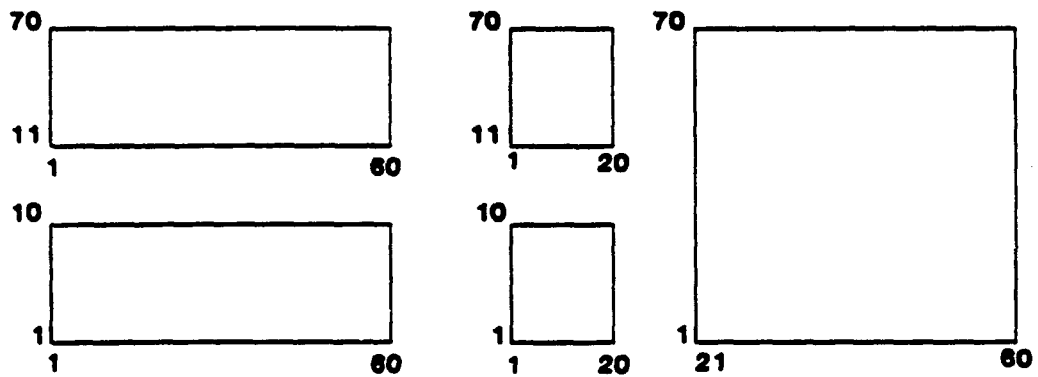


I-Patches          J-Patches

**Figure 2b.** Grid Patches Employed for Flux Calculation.

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STAGNATION ENTHALPY
2D MUZZLE BLAST
TIME = 2 MS
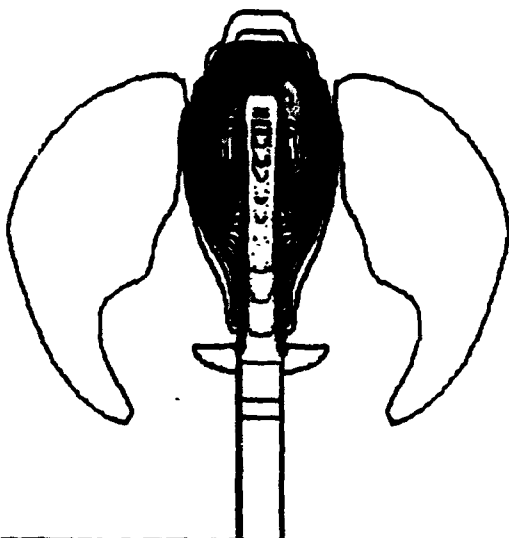
STAGNATION ENTHALPY
2D MUZZLE BLAST
TIME = 3 MS
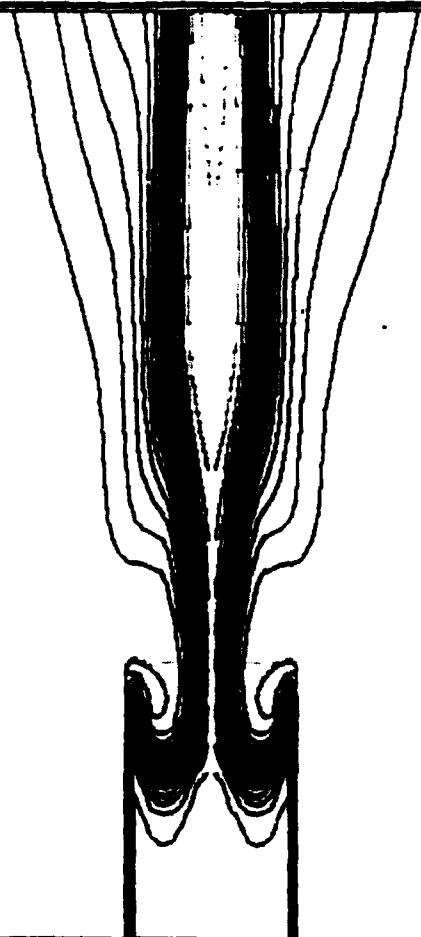
STAGNATION ENTHALPY
2D MUZZLE BLAST
TIME = 1 MS
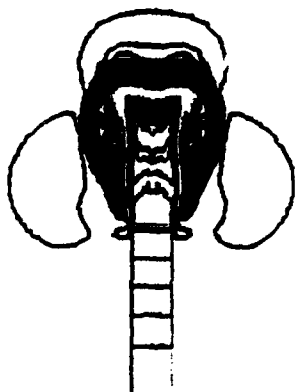
STAGNATION ENTHALPY
2D MUZZLE BLAST
TIME = 3 MS
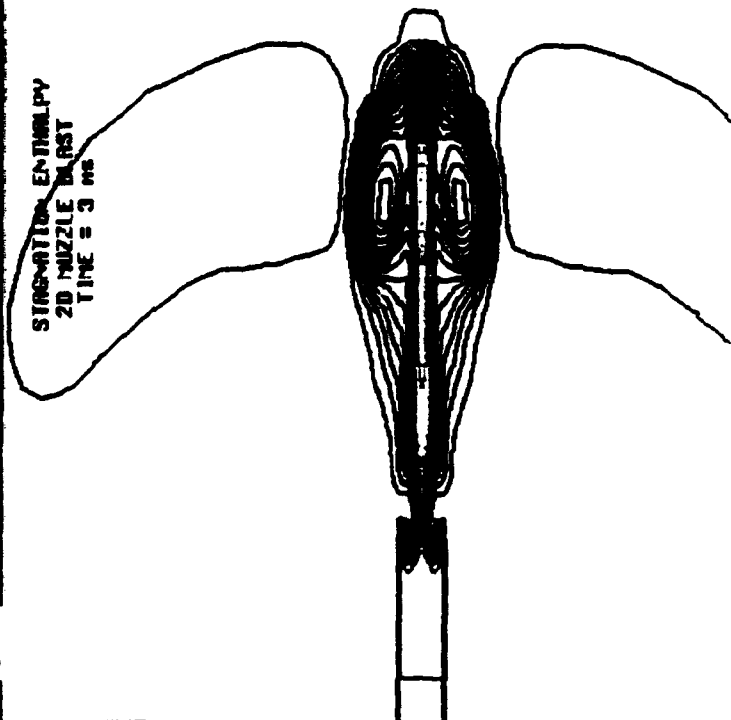
# DENSE-GAS MODELING CAPABILITIES

- REAL GAS EFFECTS AT HIGH PRESSURES AND TEMPERATURES ARE MODELED BY INCORPORATING THE VIRIAL EOS

- THE VIRIAL EQUATION OF STATE FOR A MULTI-COMPONENT GAS MIXTURE IS GIVEN BY:

$$P = \bar{R}T \sum_n \frac{\rho_i}{w_i} \left[ 1 + B_m(T) \sum_n \rho_i + C_m(T) \sum_n (\rho_i)^2 \right]$$

THE SECOND AND THIRD VIRIAL COEFFICIENTS FOR THE MIXTURE ARE RELATED TO THE INDIVIDUAL SPECIES VIRIAL COEFFICIENTS. IN GENERAL

$$B_m(T) = \sum_{ij} B_{ij} X_i X_j$$

HOWEVER, IF DATA IS UNAVAILABLE FOR CROSS COEFFICIENTS SUCH AS $B_{ij}$, WE APPROXIMATE THE RELATIONSHIP BY

$$B_m(T) = \sum_i B_i Y_i \quad \{\text{suggested by Eli Freedman}\}$$

WHERE $y_i$ IS THE MASS FRACTION.

THE VIRIAL COEFFICIENTS FOR EACH INDIVIDUAL COMPONENT CAN BE SPECIFIED IN TABULAR FORM AS A FUNCTION OF TEMPERATURE

- TEST CASES: HIGH PRESSURE SHOCK TUBE STUDIES

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# PLASMA COUPLING PROCEDURE



CRAFT
MULTI-DIMENSIONAL
SIMULATION FOR
GUN CHAMBER

COUPLING
BOUNDARY

POWELL'S QUASI-
STEADY 1D PLASMA
CODE FOR CAPILLARY

CRAFT
CODE

PLASMA
CODE

VELOCITY, TEMPERATURE AND
PRESSURE (IF CHOKED)
COMPUTED BY PLASMA
CODE/SPECIFIED AS INJECTION
CONDITION TO CRAFT

$U_{PL}$, $T_{PL}$, $P_{PL}$

PRESSURE AT COUPLING PLANE
COMPUTED BY CRAFT SPECIFIED
AS BOUNDARY CONDITION
TO PLASMA CODE

$P(t)$

$I(t)$

CURRENT SPECIFIED
AS INPUT FROM
EXPERIMENTAL DATA

51

# INFLOW MACH NUMBER HISTORY FOR PLASMA



MACH NUMBER FOR PLASMA
WHEN COUPLED TO CRAFT CODE

MACH NUMBER FOR PLASMA
GIVEN EXPERIMENTAL
PRESSURE HISTORY

M

TIME (IN MS)
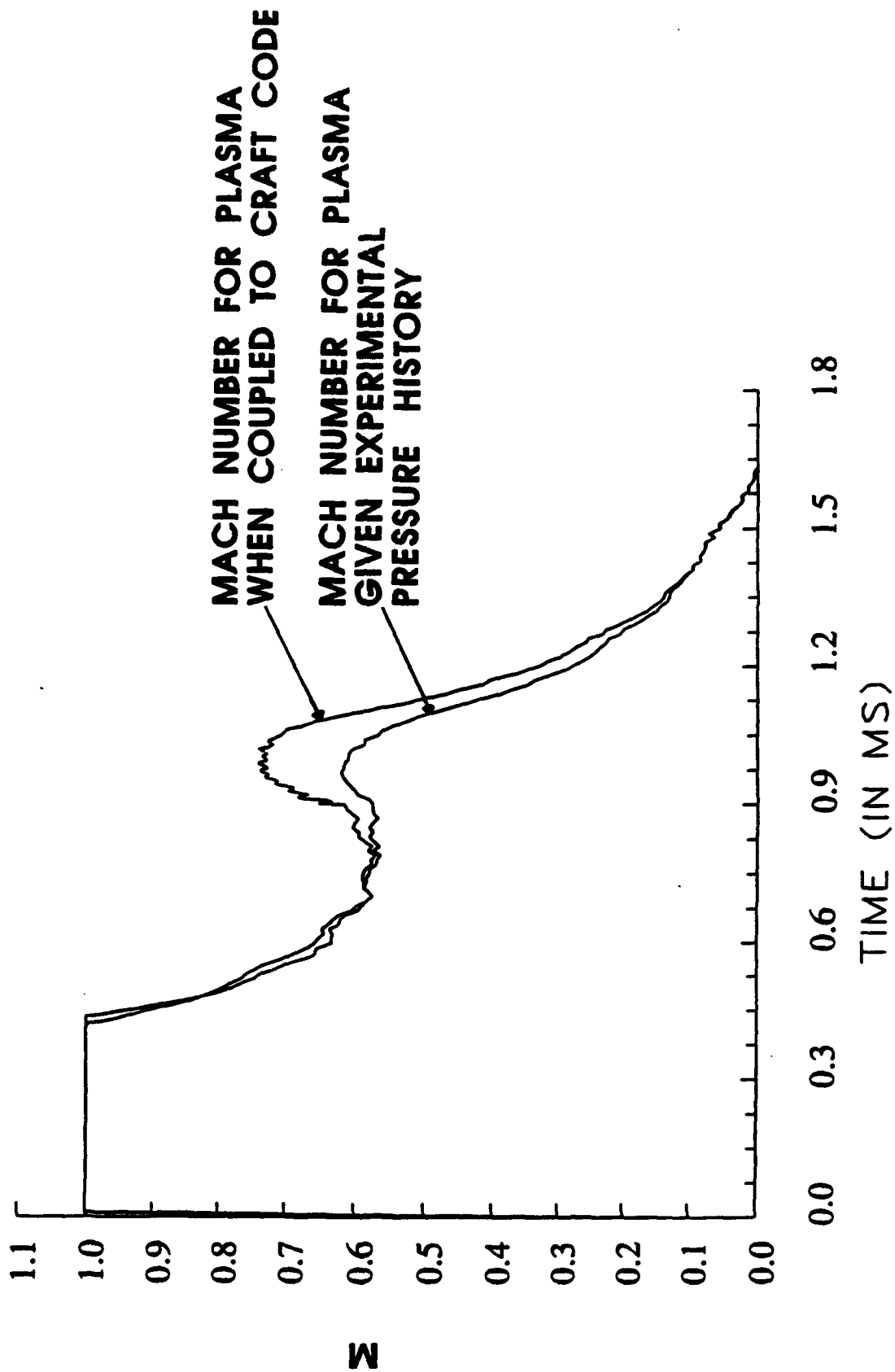
# ETC PROCESS

- Initial Configuration
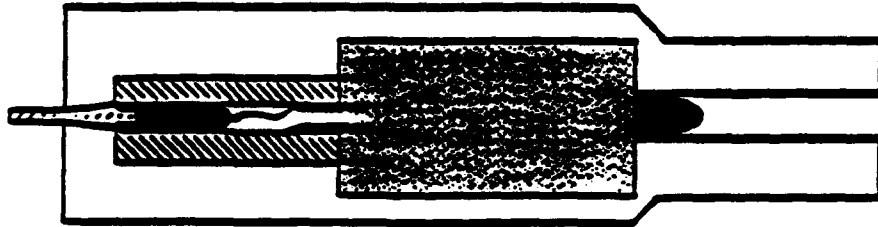
- Initiation of Plasma into Working Fluid
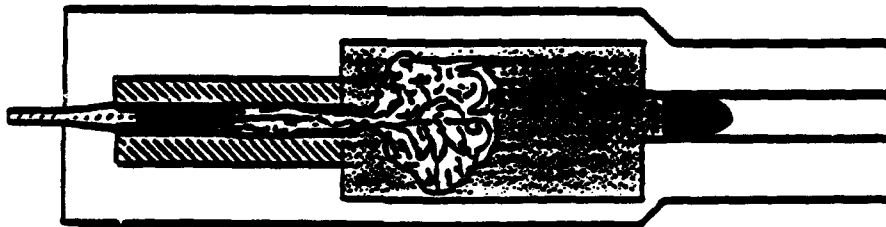
- Interaction/ Combustion/ Vaporization of Plasma and Working Fluid
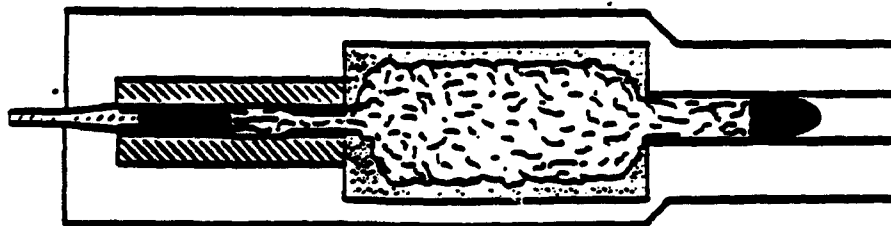
# GAS-LIQUID EQUILIBRIUM FORMULATION

| | |
|---|---|
| $P_L$, $\vec{U}_L$, $T_L$, $V_L$ LIQUID | GAS $P_G$, $\vec{U}_G$, $T_G$, $V_G$ |

- TWO-PHASE MIXTURE IS GOVERNED BY *AMAGAT'S LAW*

  TOTAL VOLUME = SUM OF PARTIAL VOLUMES

  $$\phi_G + \phi_L = 1$$

  PRESSURE IS IDENTICAL IN BOTH PHASES

  $$P_G = P_L$$

- GAS AND LIQUID PHASES TAKEN TO BE IN EQUILIBRIUM

  $$\vec{U}_G = \vec{U}_L$$

  $$T_G = T_L$$

THIS ALLOWS US TO FORMULATE GLOBAL CONSERVATION EQUATIONS FOR THE MIXTURE RATHER THAN SEPARATE EQUATIONS FOR EACH PHASE

# HOW DO WE OBTAIN THE DERIVATIVES OF THE PRESSURE TERM?

THE GAS AND LIQUID PRESSURES ARE FUNCTIONS OF THREE VALUES:

$$P_G = f(\hat{\rho}_g, T, \phi_g), \ P_L = f(\hat{\rho}_L, T, (1 - \phi_g))$$

$$dP_g = f(d\hat{\rho}_g, dT, d\phi_g)$$

$$dP_L = f(d\hat{\rho}_L, dt, d(1 - \phi_g))$$

SINCE WE DO NOT SOLVE DIRECTLY FOR $\phi_g$, WE ELIMINATE THE $d\phi_g$ TERM BY EVALUATING $dP_g = dP_L$ AND GETTING AN EXPRESSION FOR $d\phi_g$.

USING THIS RELATIONSHIP FOR $d\phi_g$, IT IS STRAIGHTFORWARD TO DERIVE THE DERIVATIVES OF THE PRESSURE

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# SPEED OF SOUND IN TWO-PHASE SYSTEM

- **CALCULATE EIGENVALUES OF THE FLUX JACOBIAN A:**

$$A - \lambda I = 0$$

- **EIGENVALUES OF A ARE EVALUATED TO BE:**

$$\Lambda = [\hat{U} + k_\xi C, \hat{U} - k_\xi C, \hat{U}, \hat{U}, \ldots \hat{U}]^T \quad \{k_\xi = [\tilde{\xi}_x^2 + \tilde{\xi}_y^2 + \tilde{\xi}_z^2]^{\frac{1}{2}}\}$$

**WHERE, C, THE SPEED OF SOUND IN THE MIXTURE IS:**

$$C_m = \left\{ \frac{\tilde{\gamma}}{\rho_m} \left[ \frac{\phi_g}{\rho_g C_g^2} + \frac{1 - \phi_g}{\rho_L C_L^2} \right]^{-1} \right\}^{\frac{1}{2}}$$

$$C_g = \text{Isothermal Speed of Sound in Gas} = \left( \frac{\partial P_g}{\partial \rho_g} \right)_T^{\frac{1}{2}}$$

$$C_L = \text{Isothermal Speed of Sound in Liquid} = \left( \frac{\partial P_L}{\partial \rho_L} \right)_T^{\frac{1}{2}}$$

# VALIDATION STUDIES FOR GAS-LIQUID FORMULATION

- SOLUTIONS FOR TWO-PHASE 1-D SHOCK TUBES WERE COMPARED WITH TERRY COFFEE'S COMPUTATIONS

| 50 MPa | 100 MPa |
|--------|---------|

**CASE I**   LIQUID – HIGH PRESSURE SIDE
GAS – LOW PRESSURE SIDE

**CASE II**   LIQUID – LOW PRESSURE SIDE
GAS – HIGH PRESSURE SIDE

**CASE III**   UNIFORM MIXTURE OF GAS AND LIQUID ON BOTH SIDES

**CASE IV**   RADIAL SHOCK TUBE – UNIFORM MIXTURE WITH HIGH PRESSURE AT CORE

HIGH PRESSURE

# PRESSURE PROFILES FOR A TWO-PHASE SHOCK TUBE

## Gas = High Pressure Side and Liquid = Low Pressure Side
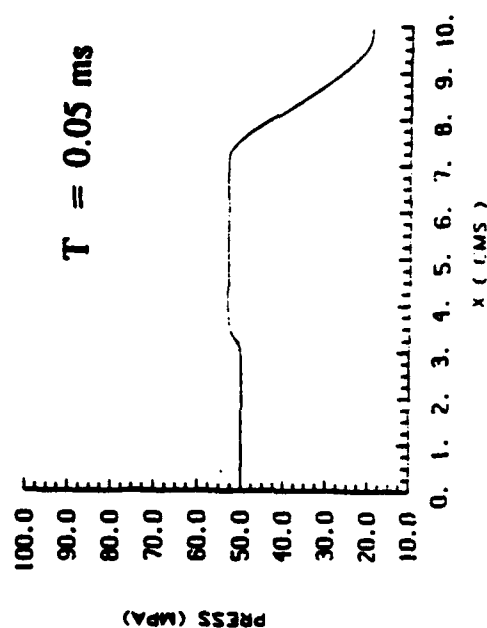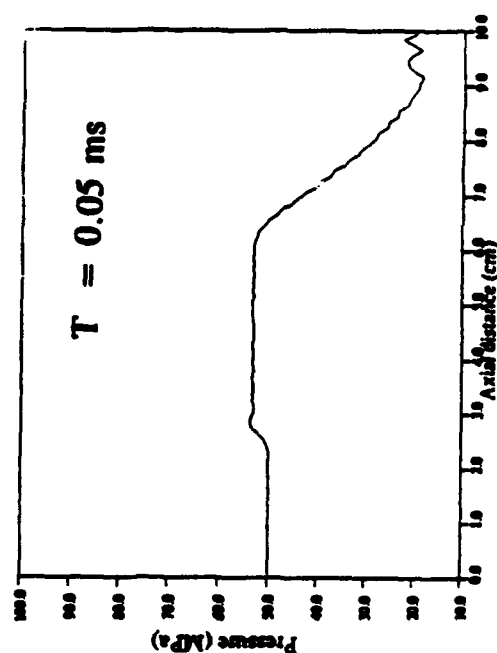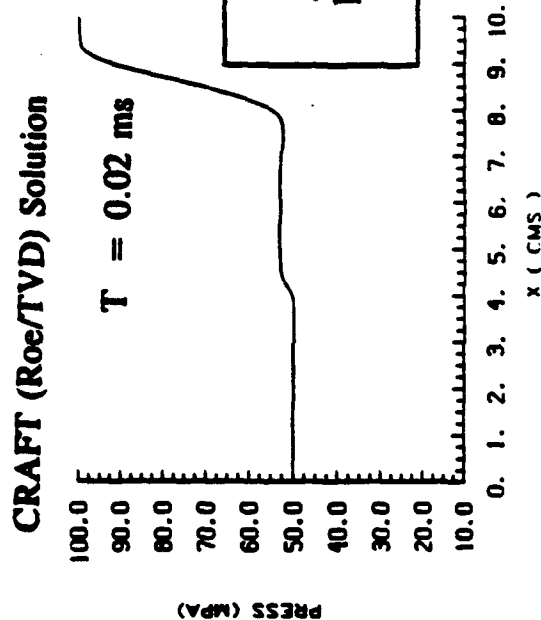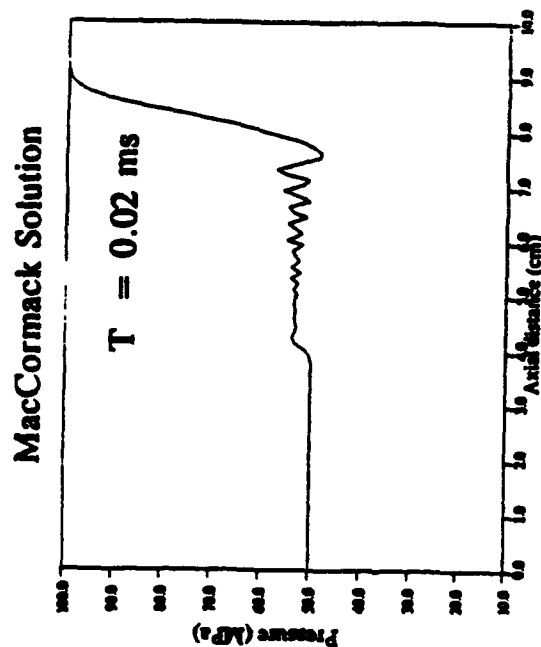
# PRESSURE PROFILES FOR A TWO-PHASE SHOCK TUBE

## Gas = Low Pressure Side and Liquid = High Pressure Side

# PRESSURE PROFILES FOR A TWO-PHASE SHOCK TUBE

## Uniform Gas/Liquid Mixture



CRAFT (Roe/TVD) Solution
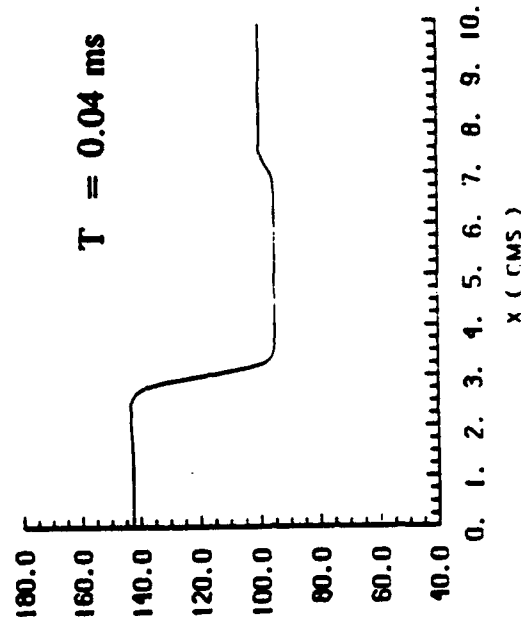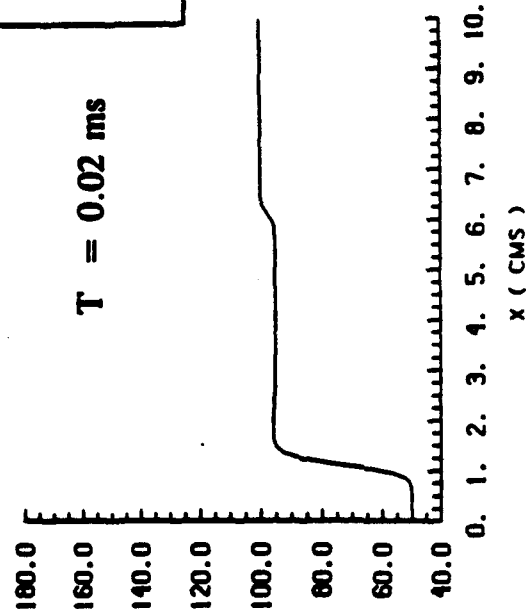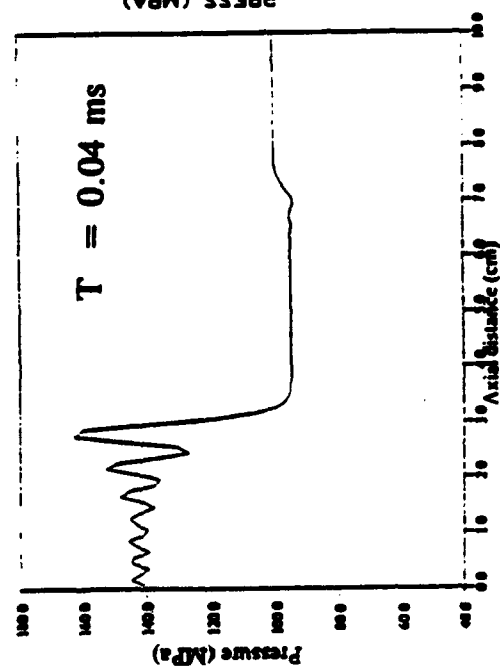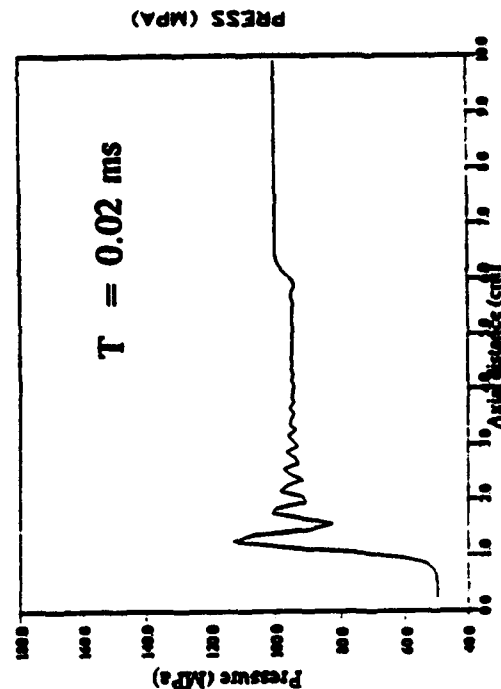
MacCormack Solution

# PRESSURE HISTORY ON WALL OF TWO-PHASE SHOCK TUBE

## Uniform Gas/Liquid Mixture
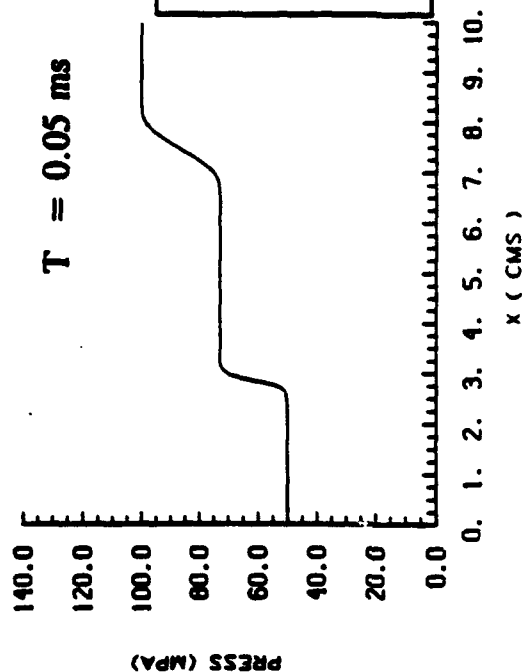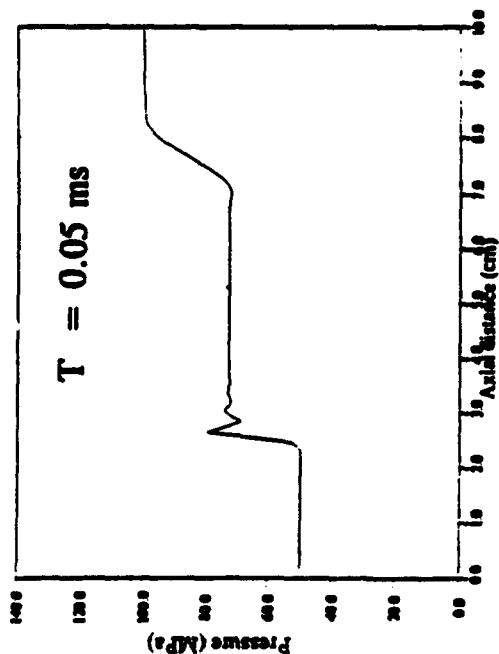
| 50 MPa | 100 MPa |
|---|---|
| G/L Mixture $\phi_g = 0.501$ | G/L Mixture $\phi_g = 0.501$ |

——— Left Wall

------- Right Wall

CRAFT (Roe/TVD) Solution



MacCormack Solution



62
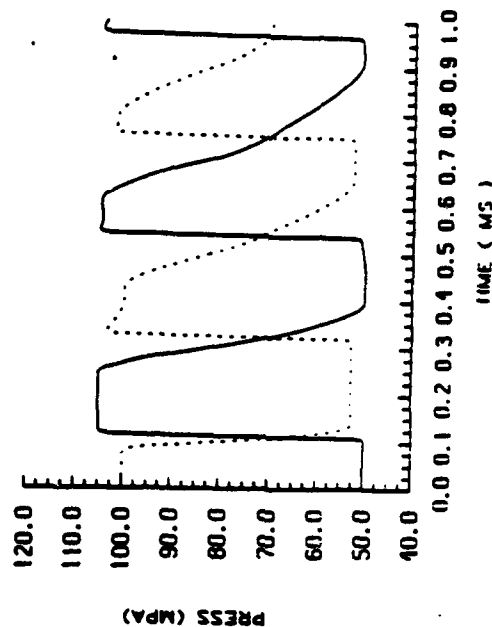
# PRESSURE HISTORY FOR A RADIAL TWO-PHASE SHOCK TUBE

## Uniform Gas/Liquid Mixture



63
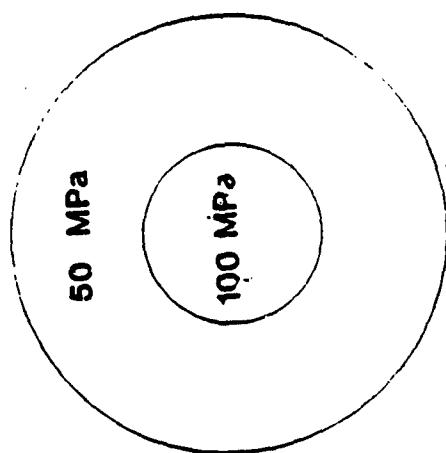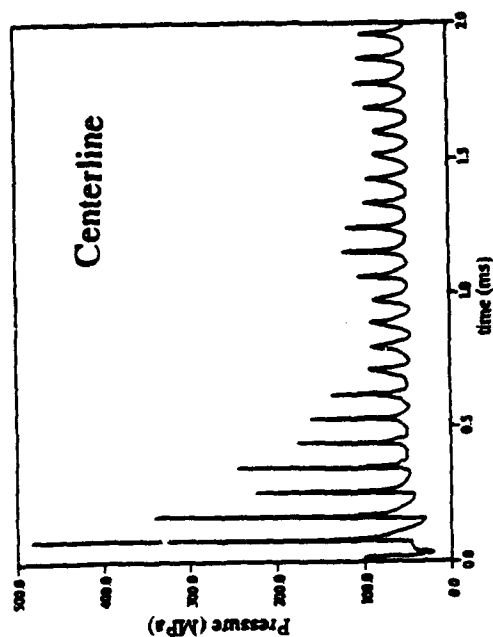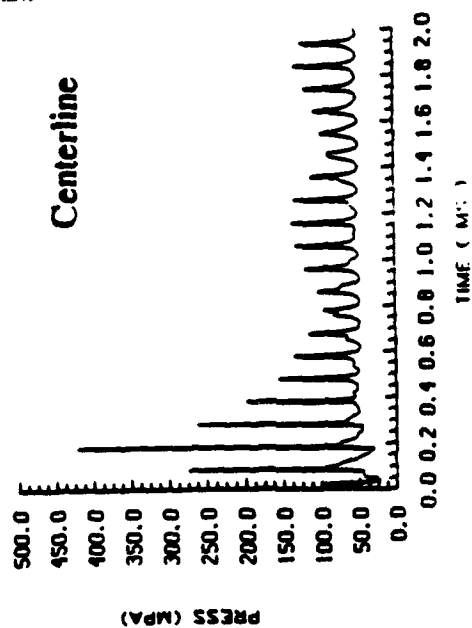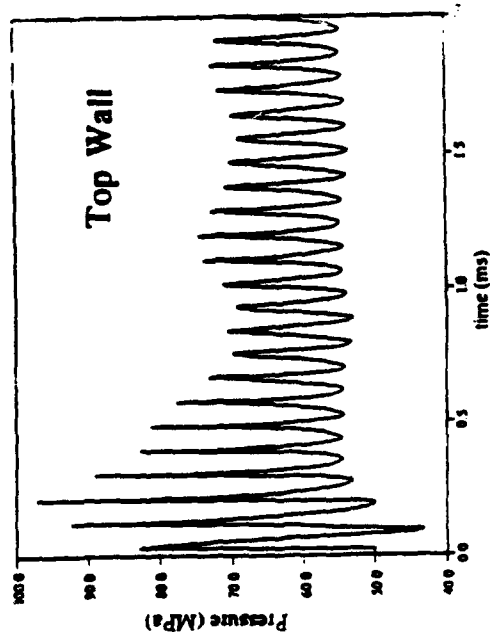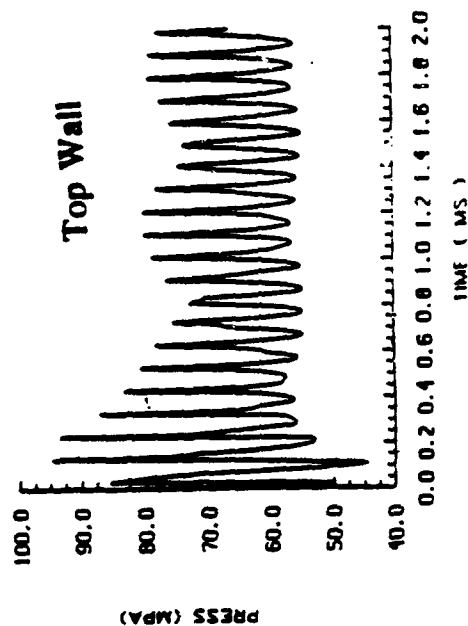
# FREQUENCY SPECTRA FOR A RADIAL TWO-PHASE SHOCK TUBE
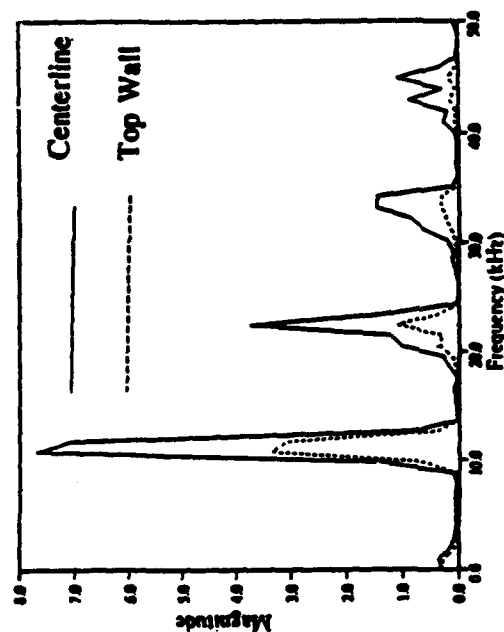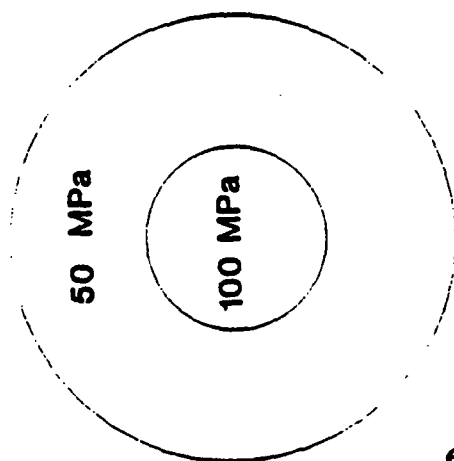
## Uniform Gas/Liquid Mixture



64
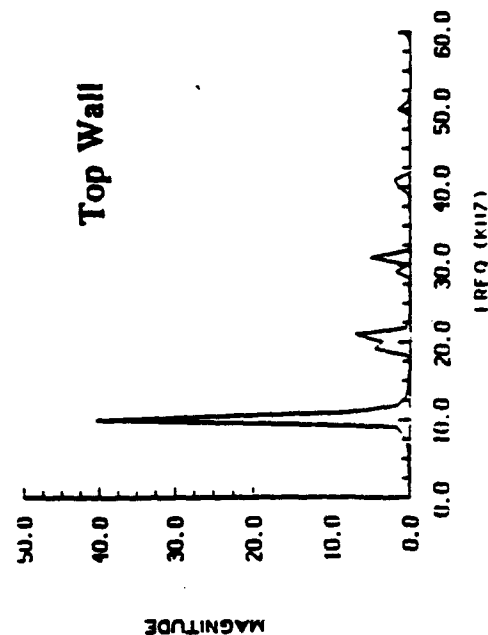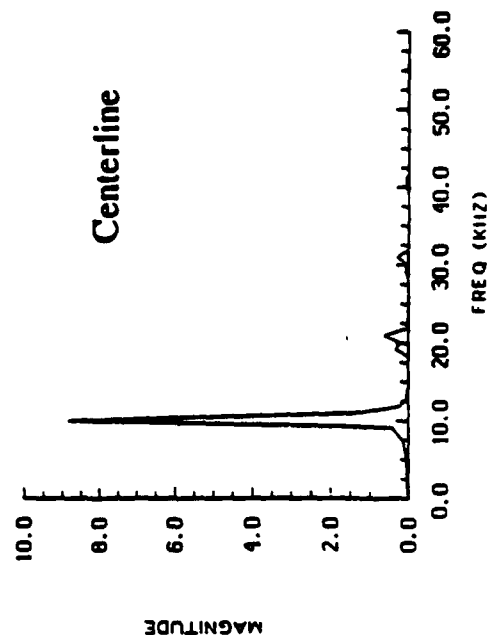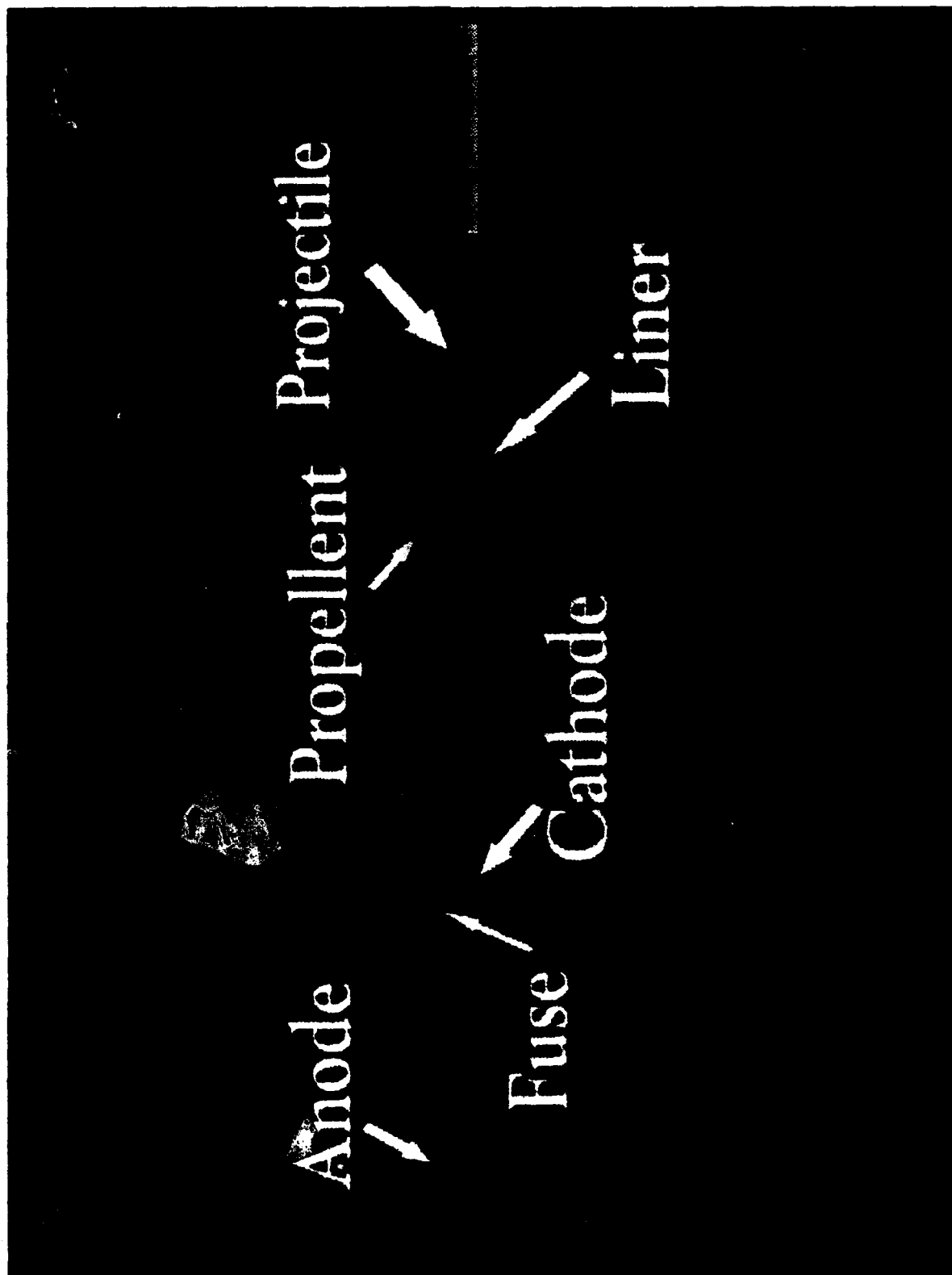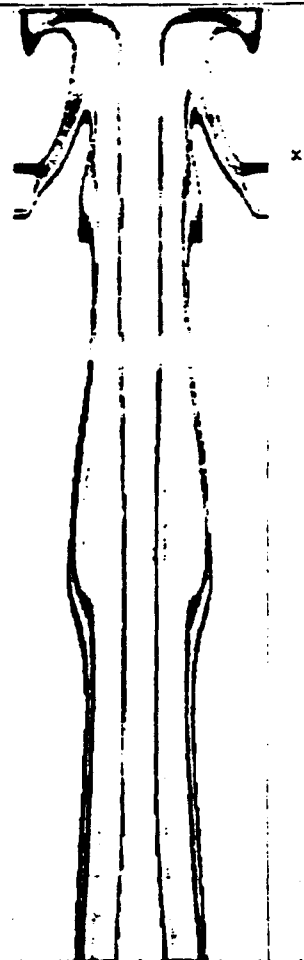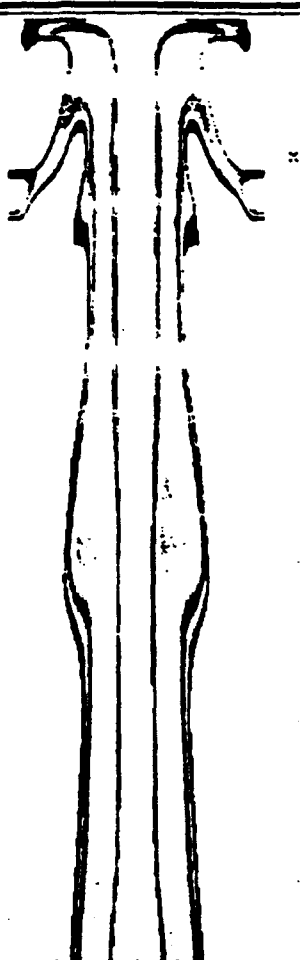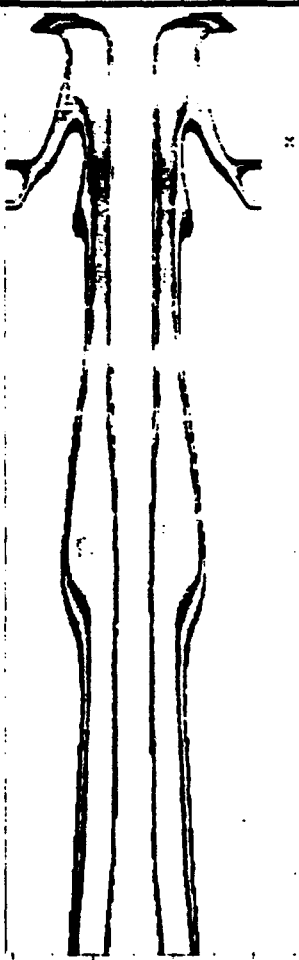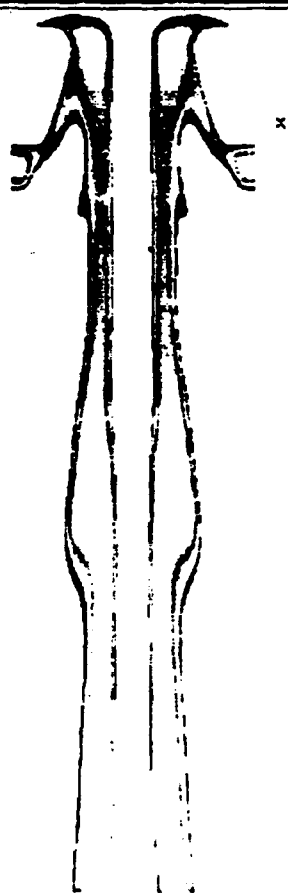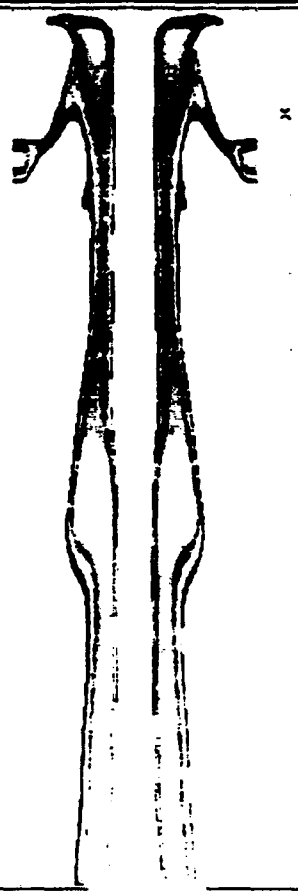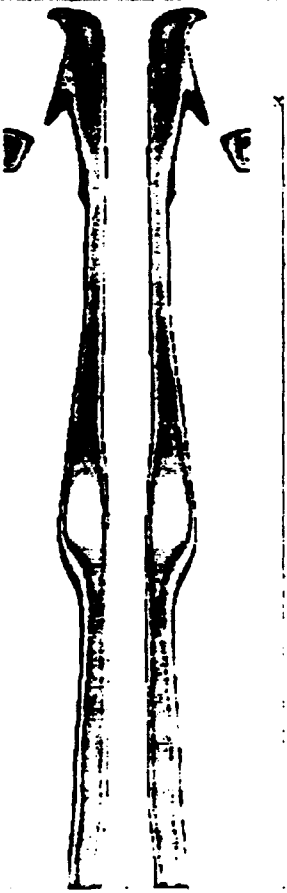
# TURBULENCE CHARACTERISTICS IN ULLAGE TUBE
## 17.5 cms FROM PROJECTILE BASE

**(A)  Radial Variation of U_rms**

$(A)$  Radial Variation of $U_{rms}$

**(B)  Instantaneous Axial Velocity at y=0.48 cms**
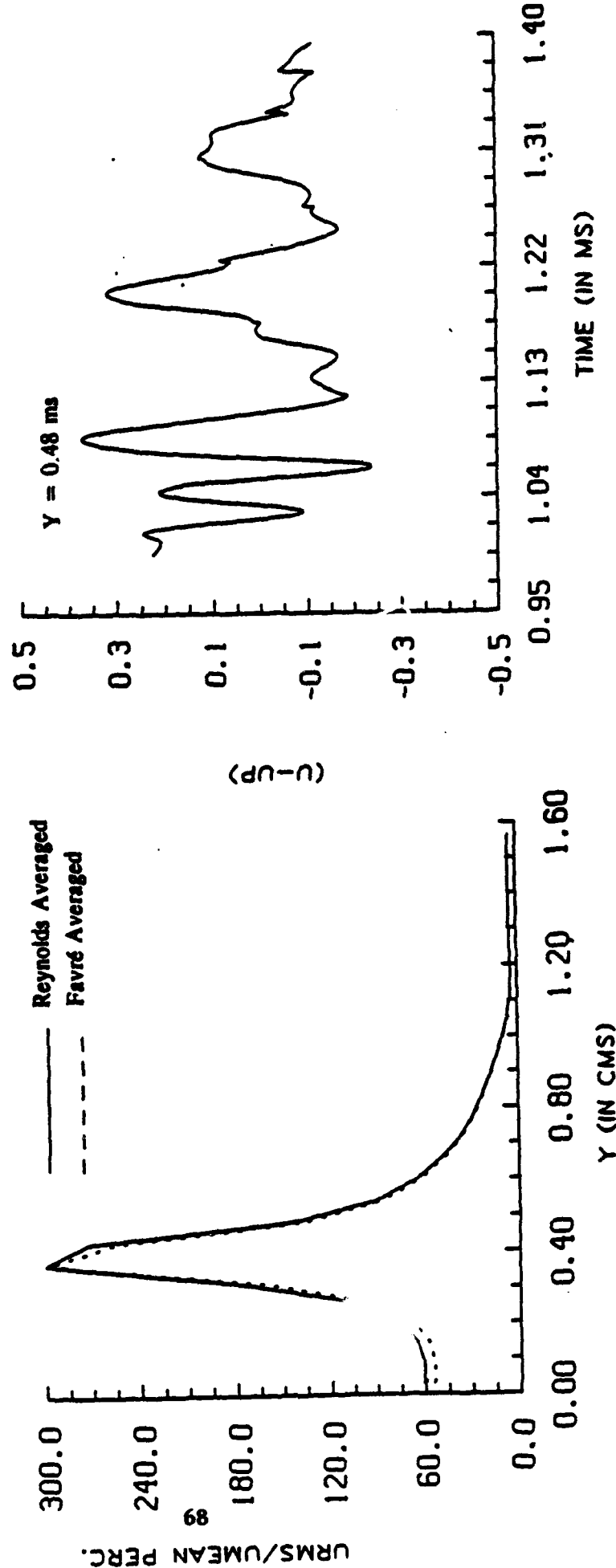
# LES vs RNS OVERVIEW / INCOMPRESSIBLE

## 1. DECOMPOSITION

- **LES** $\quad u = \bar{u} + u'$
  $\qquad \bar{u} - resolveable$
  $\qquad u' - nonresoveable$

- **RNS** $\quad u = \bar{u} + u'$
  $\qquad \bar{u} - mean$
  $\qquad u' - fluctuating$

## 2. AVERAGING

- **LES** → **SPATIAL FILTER TO ELIMINATE HIGH FREQUENCY COMPONENTS**

- **RNS** → **TIME-AVERAGING, INTERVAL MUST BE LARGER THAN CONVECTIVE MOTION OF LARGE SCALE STRUCTURE; NOT APPLICABLE FOR SHORT-DURATION FLOWS**

## 3. TERMS FROM AVERAGING

- **LES** $\quad \overline{u_i' u_j'} + \left( \overline{\overline{u_i u_j}} - \overline{u_i}\,\overline{u_j} \right) + \left( \overline{\bar{u}_i u_j'} - \overline{u_i' \bar{u}_j} \right) \quad \rightarrow \quad$ **INVARIANT ?**

- **RNS** $\quad \overline{u_i' u_j'} \quad \rightarrow \quad$ **NOT INVARIANT, COEFFICIENTS ARE PROBLEM-DEPENDENT**

# COMPARISON OF PRESSURE HISTORY WITH
# AND WITHOUT SUBGRID TURBULENCE



70
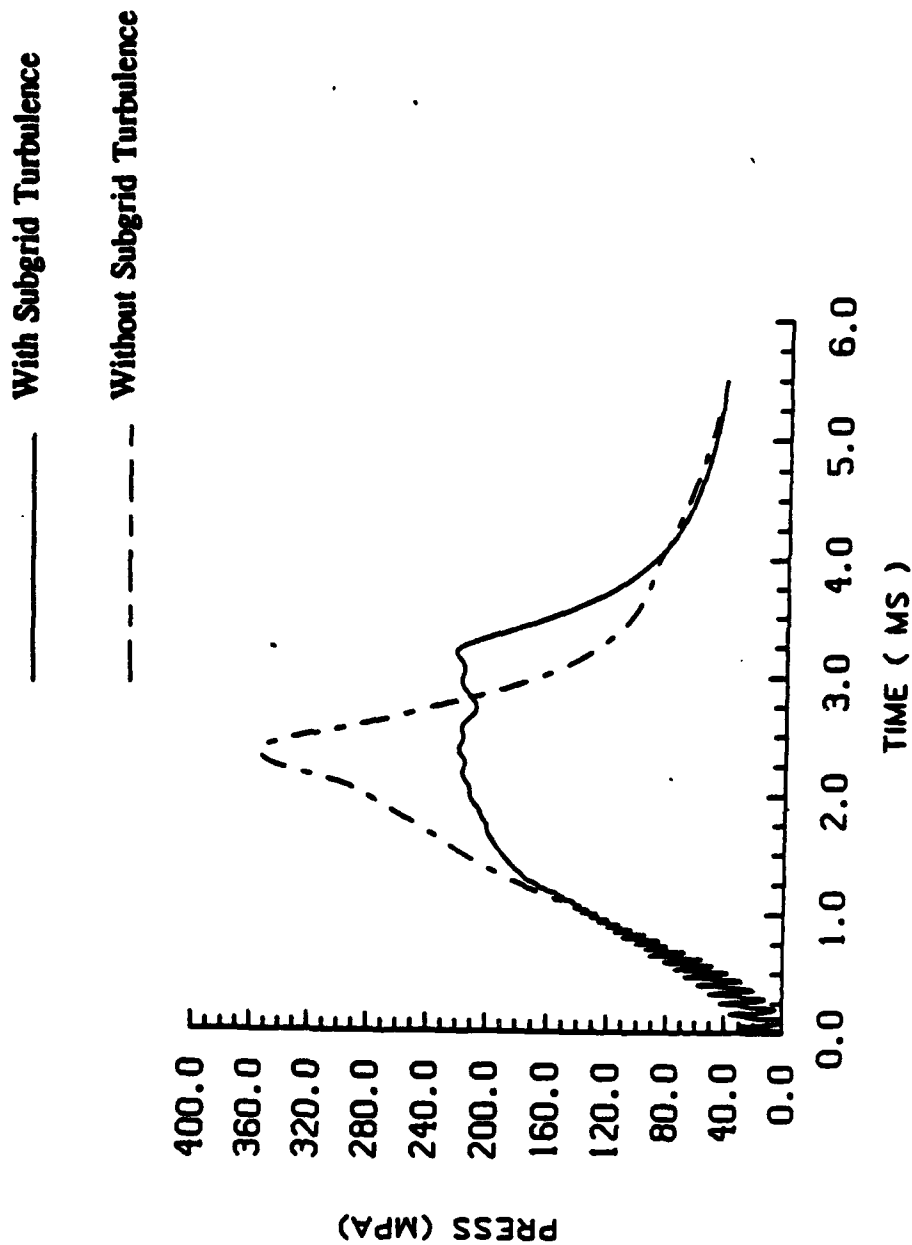
# PRESSURE HISTORY AT TAP A

## EXPERIMENTAL DATA vs NUMERICAL COMPUTATION FOR FMC SHOT 17
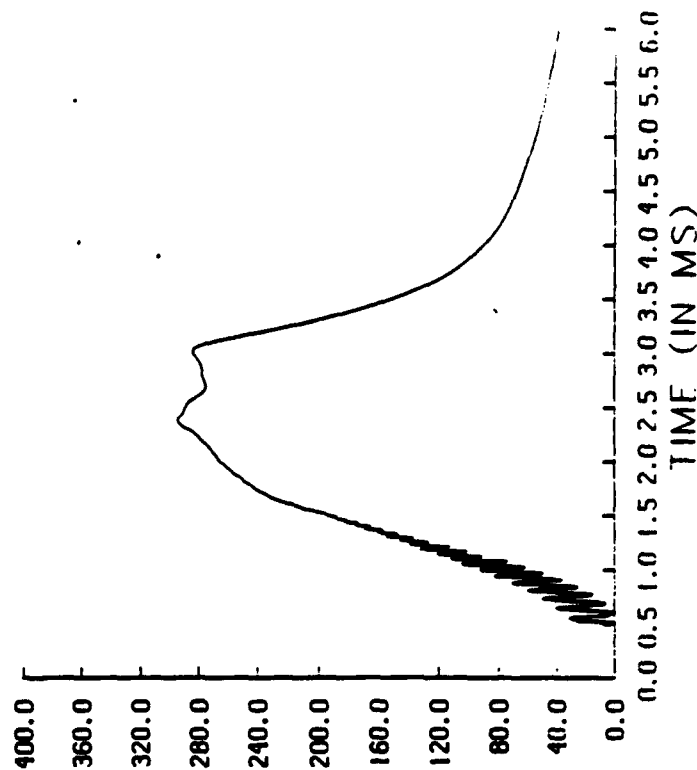
Z-COMPONENT OF VORTICITY
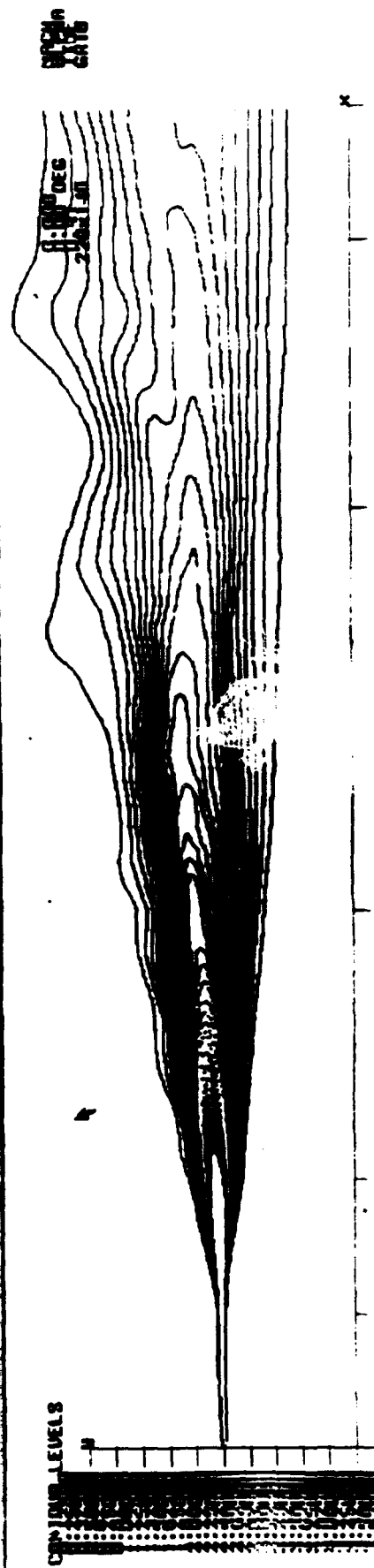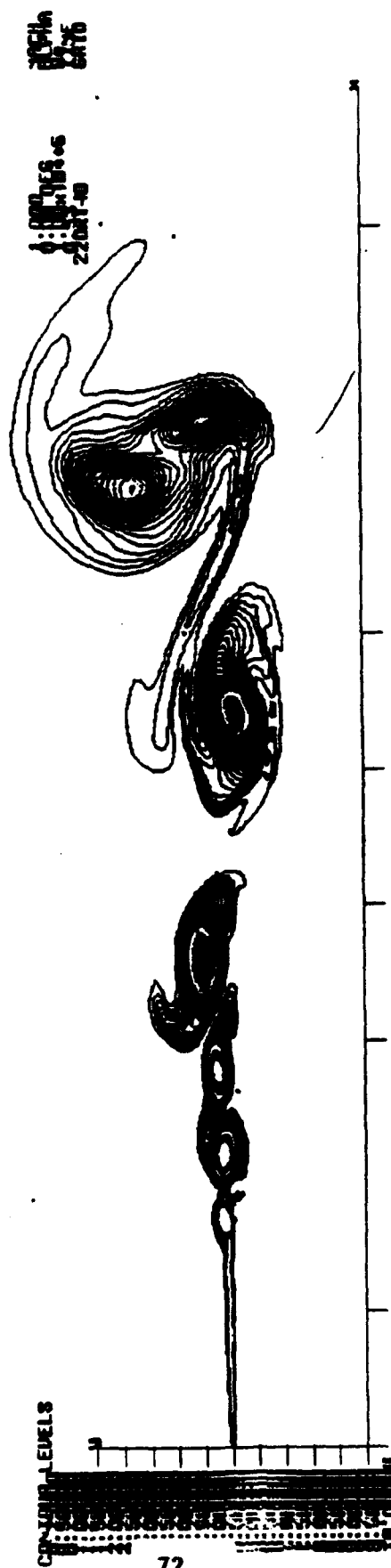
photo# lcf 1

photo# lcf 2

photo# lcf 3

73

74

Dangerous.

DENSITY at STATION # 2
MEAN and RMS FLUCTUATION

CONTOUR LEVELS

DENSITY at STATION # 1
MEAN and RMS FLUCTUATION

CONTOUR LEVELS

DENSITY at STATION # 3
MEAN and RMS FLUCTUATION

CONTOUR LEVELS
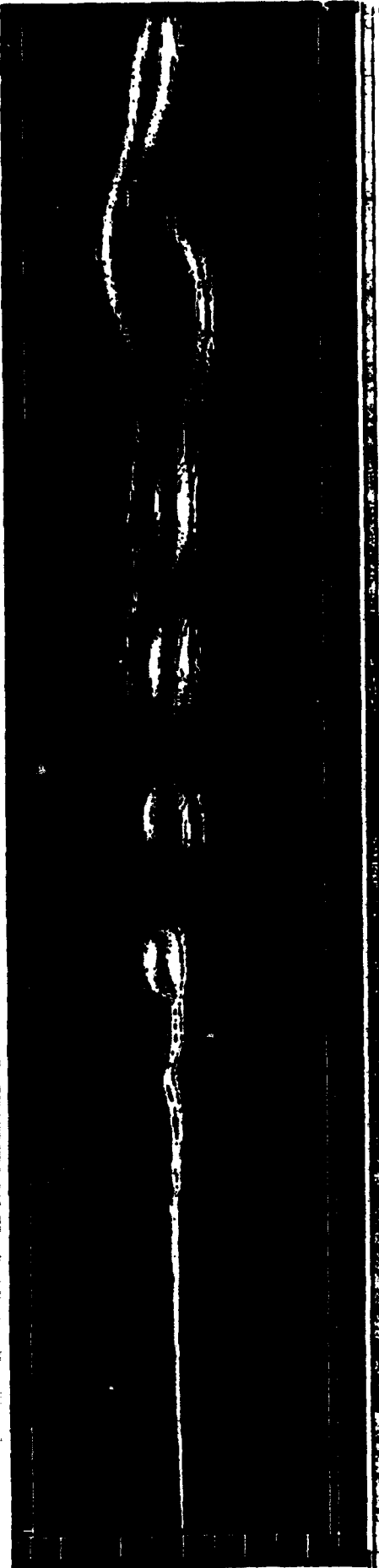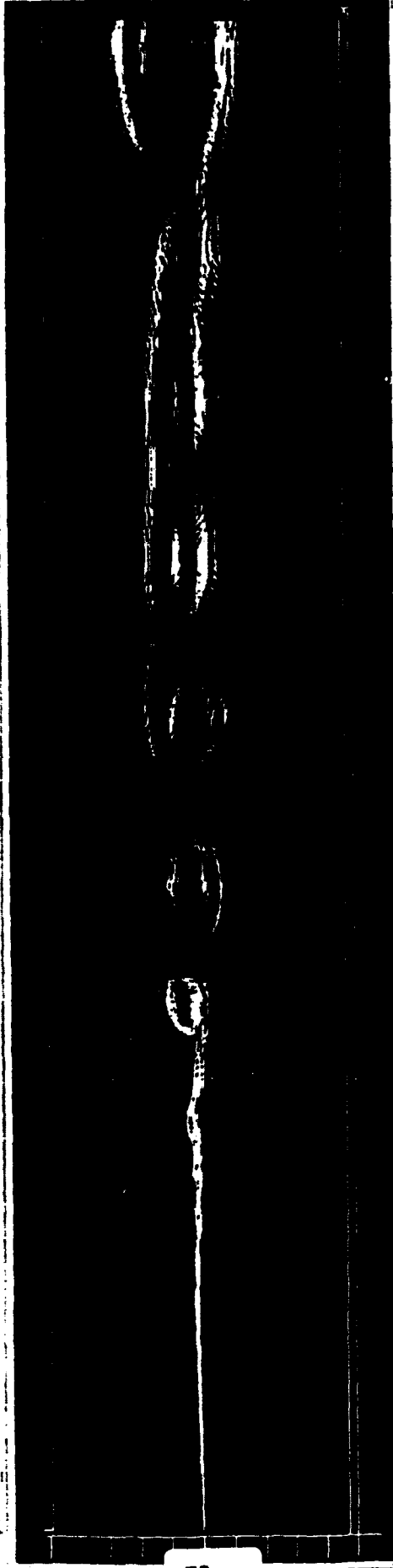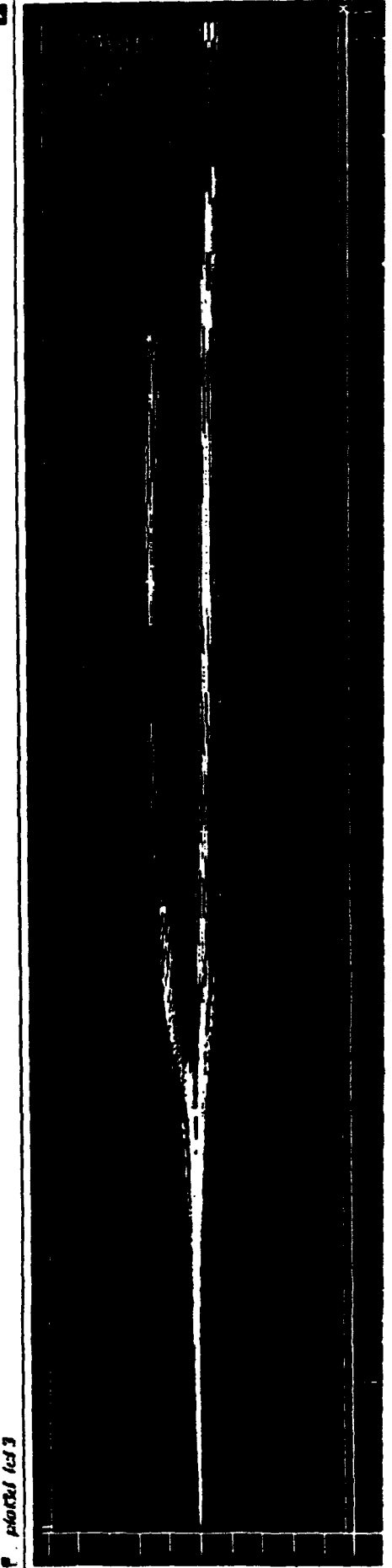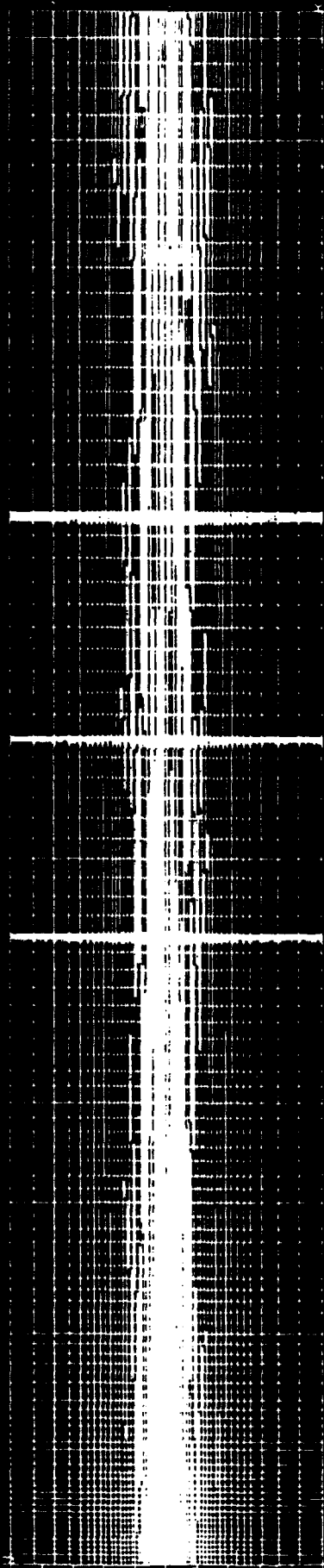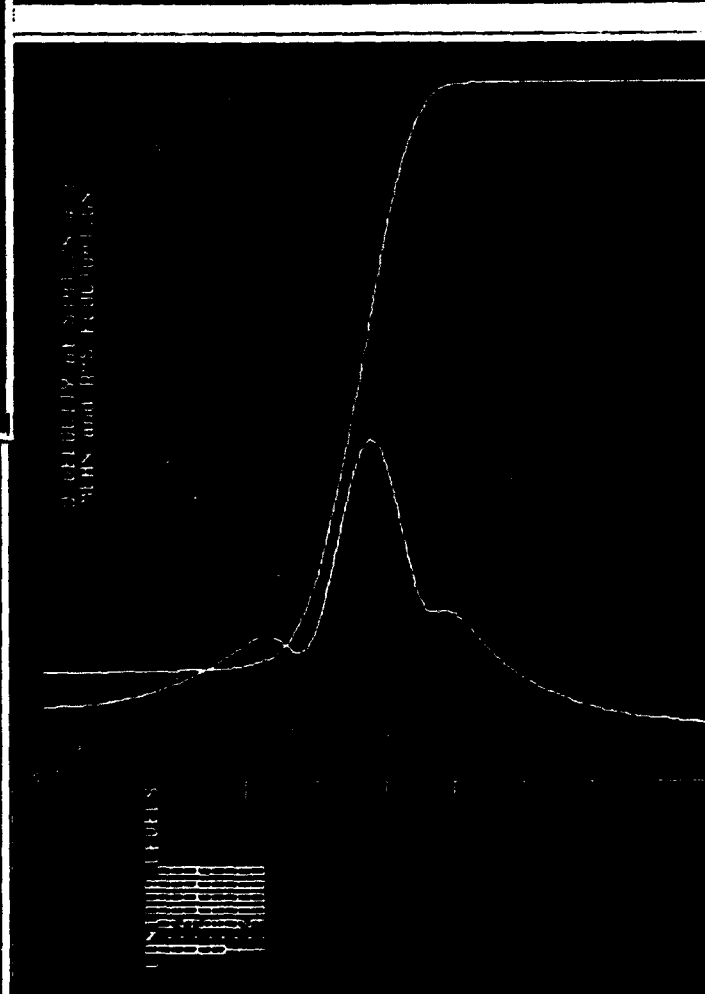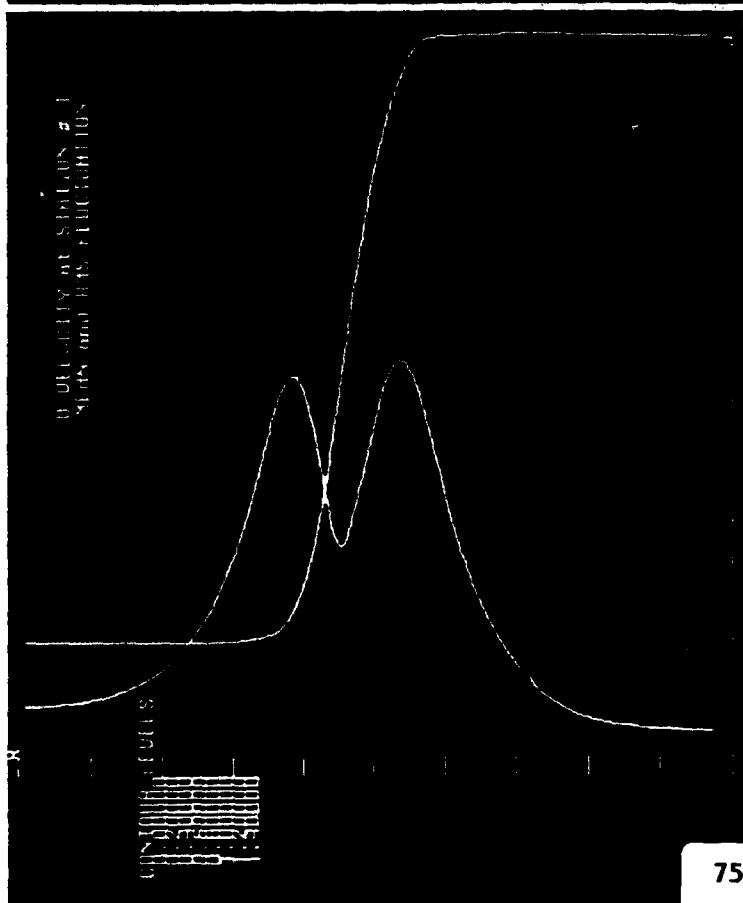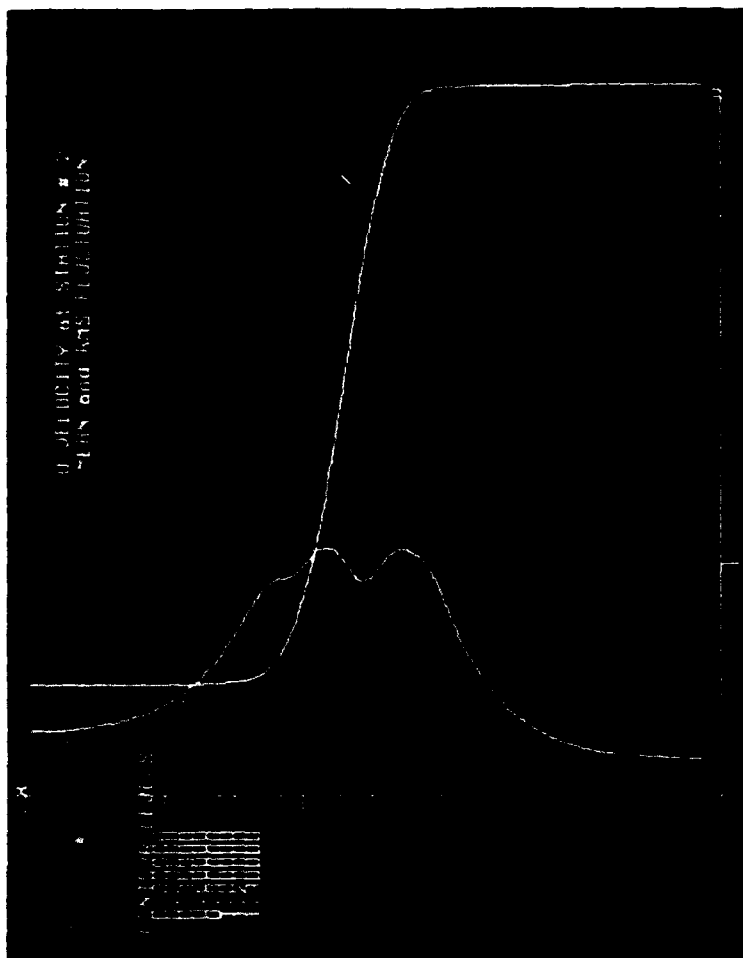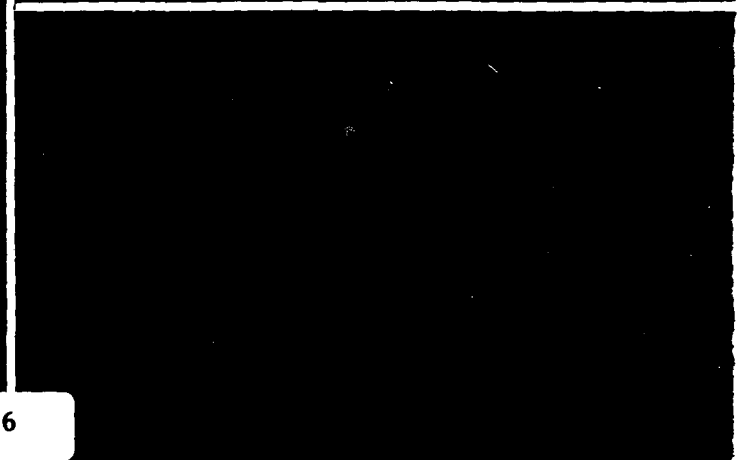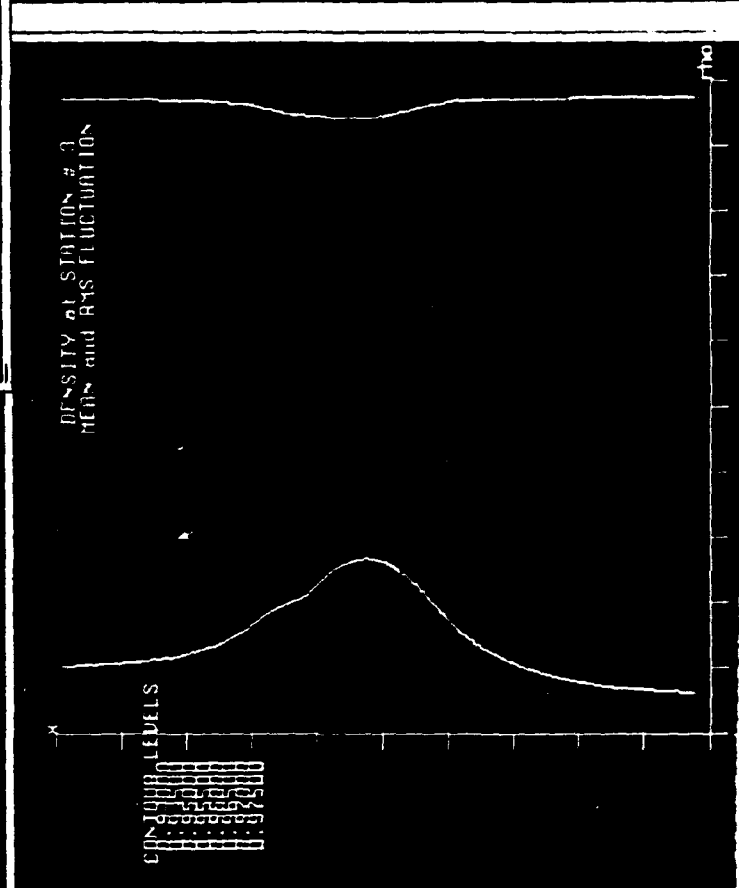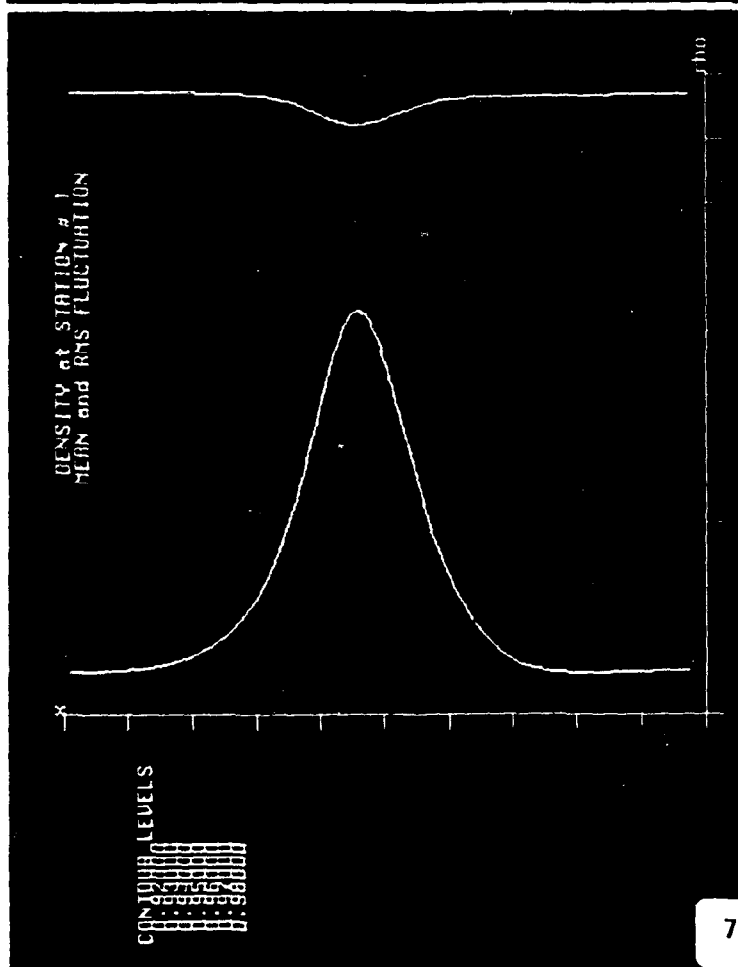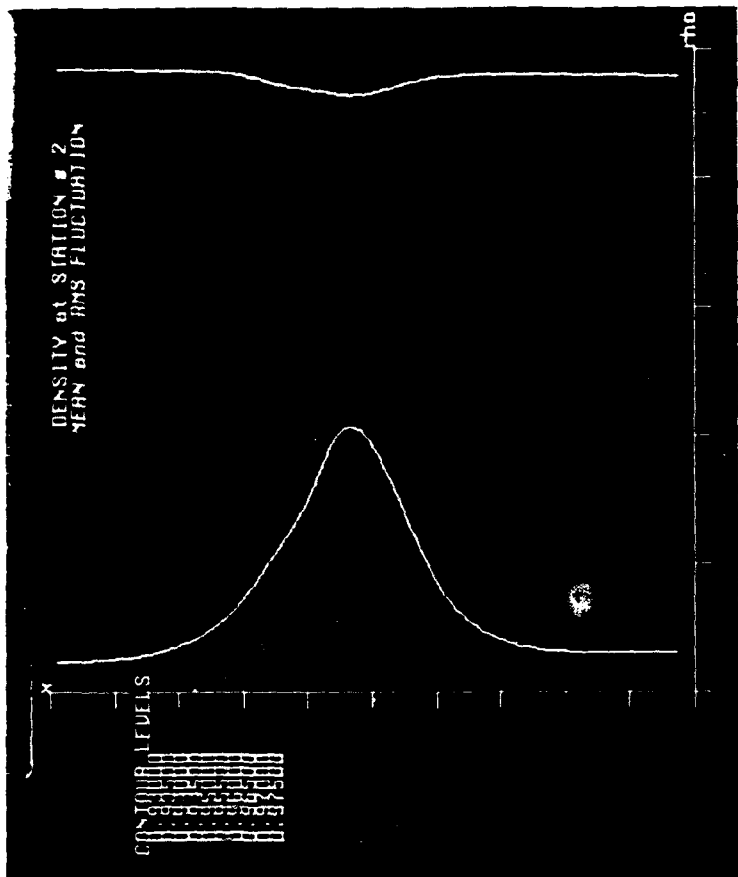
# PRELIMINARY SOLID PROPELLANT BURNING MODEL
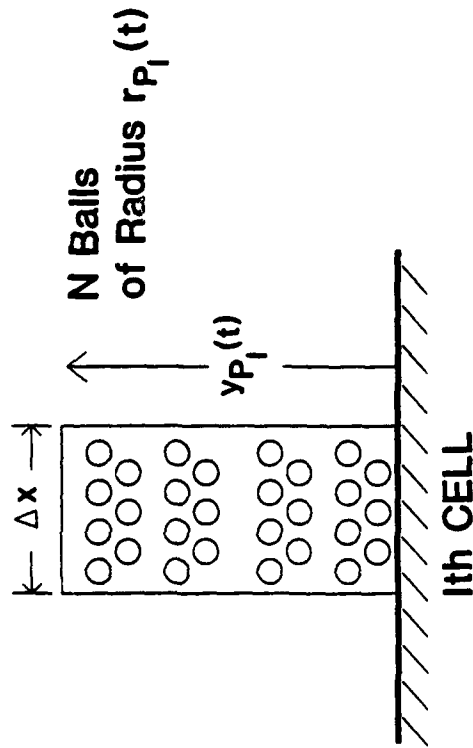
- **FIXED-BED ASSUMPTION**

- **ALL BALLS IN EACH CELL BURN AT SAME RATE**

- $r_p(t)$ **TRACKED IN EACH CELL**

- **PRESSURE DEPENDENT BURN RATE — EXTERNAL SURFACE PRESSURE UTILIZED WHICH VARIES AXIALLY**

**N Balls of Radius** $r_{P_I}(t)$

$y_{P_I}(t)$

**Ith CELL**

**MASS OF PROPELLANT IN CELL** $= M_P = \dfrac{4}{3}\pi r_p^3 \times \rho_p \times N$

**RADIUS CHANGE:** $\quad r_p \rightarrow r_p - (\dot{r})\,\Delta t \ \{\dot{r} \text{ function of pressure}\}$

**MASS CHANGE:** $\quad \dot{m} = (4\pi r_p^2)\,\dot{r}\,\rho_p \times N$

**REGRESSION VELOCITY:** $\quad V_S = \dfrac{\dot{m}}{\rho L} \ \{\rho L \text{ is loading density}\}$

**COMBUSTION PRODUCT FLUX:** $\quad \rho_g V_g = \rho_L V_S$

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# COUPLING OF SOLID PROPELLANT BURN MODEL INTO CRAFT
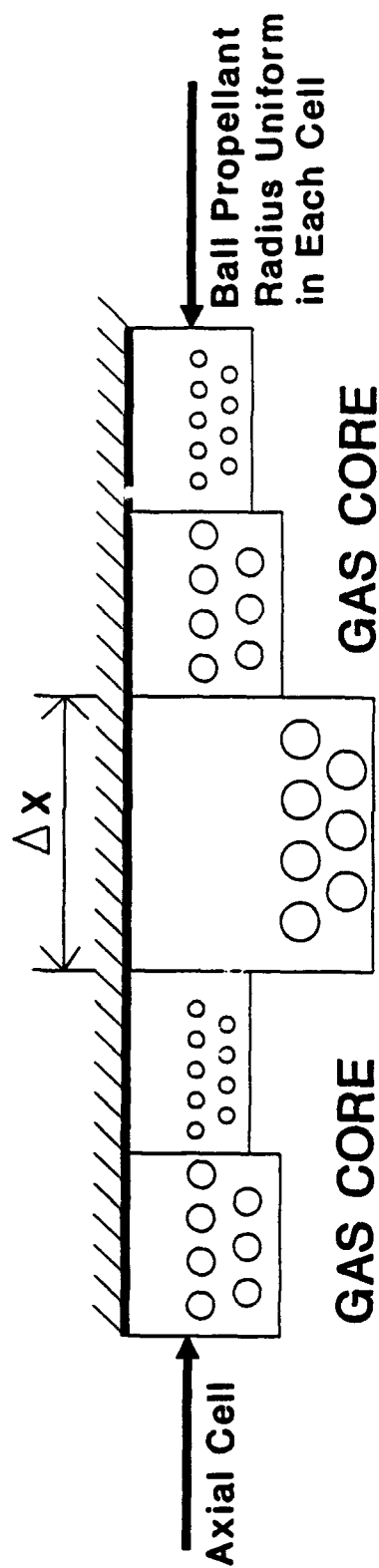


- **BURNING RATE FUNCTION OF LOCAL SURFACE PRESSURE**

- **GASEOUS PRODUCTS MASS AND ENERGY FLUXES FROM SOLID PROPELLANT SERVE AS BOUNDARY CONDITIONS**

- **DYNAMIC MOTION OF RECESSING SOLID PROPELLANT ACCOUNTED FOR**

# GDLS SHOT 45 INPUT DATA

## 15 LAYER THERMOCHEMISTRY

## CURRENT HISTORY

COMPUT VS PC1 COMPARISON
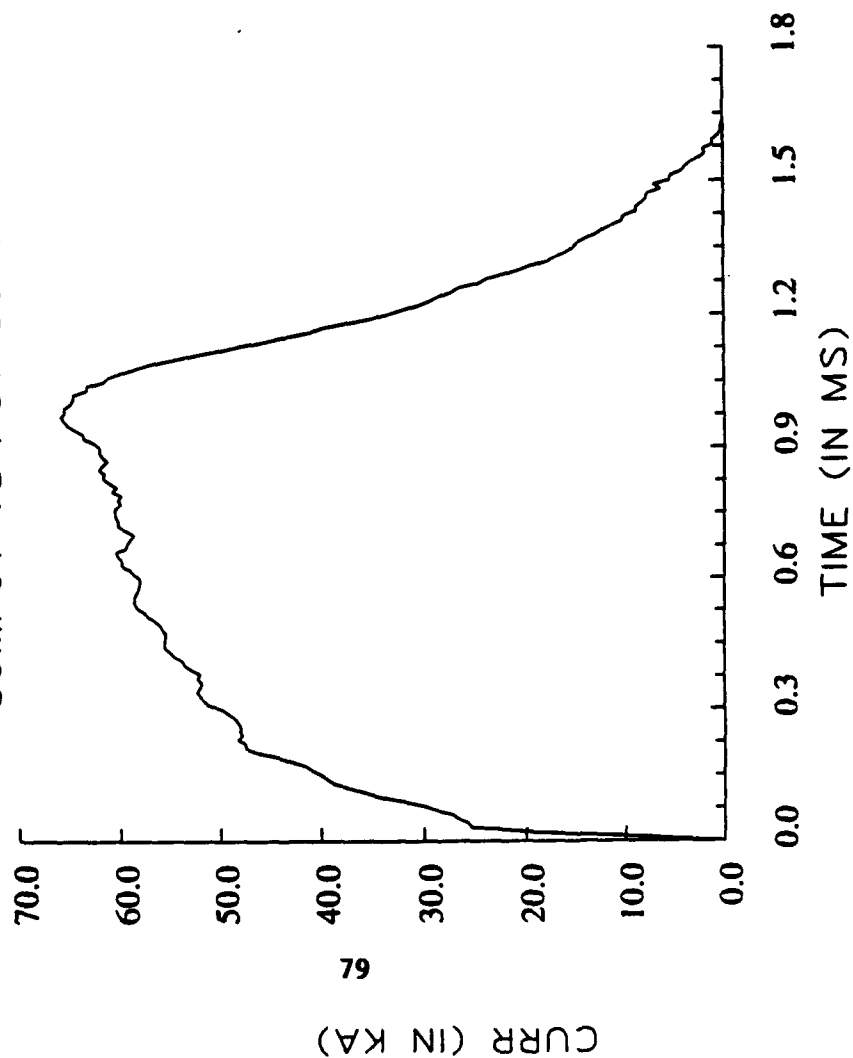
| % of Radius | Flame Temperature (K) |
|---|---|
|  |  |

CURR (IN KA)

70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0

0.0    0.3    0.6    0.9    1.2    1.5    1.8
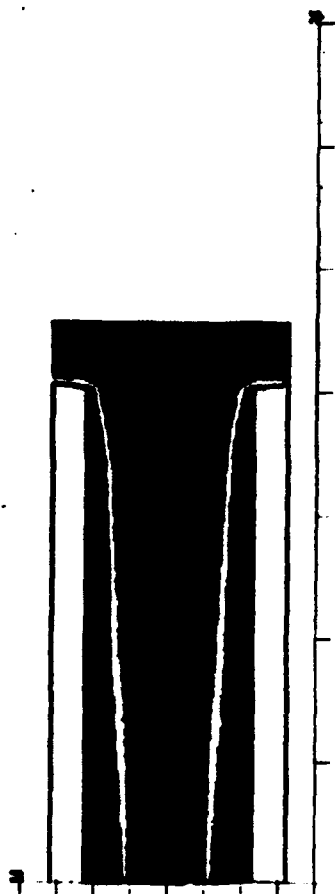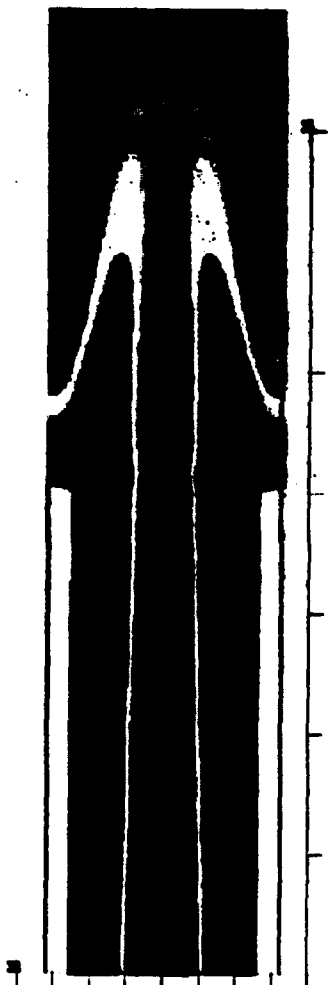
TIME (IN MS)
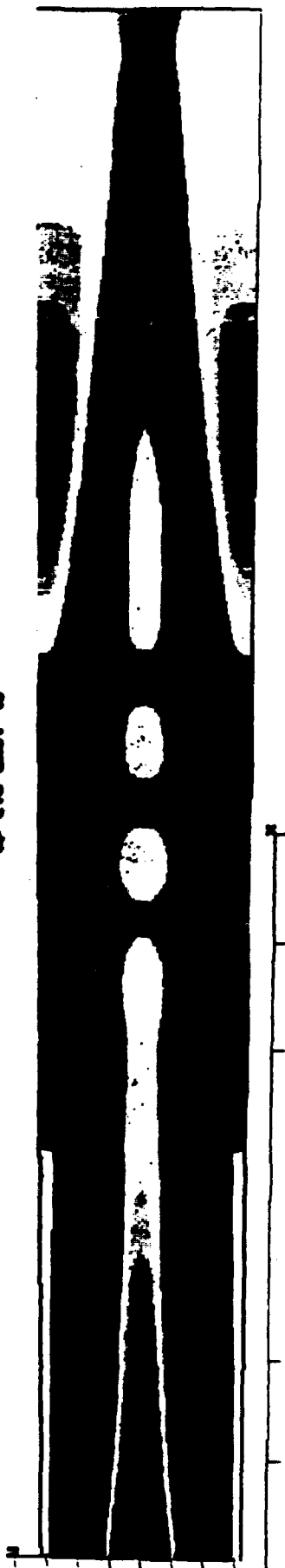
GDLS SHOT 45

PRESSURE HISTORY COMPARISON AT PORT 1

COMPUTED PRESSURE
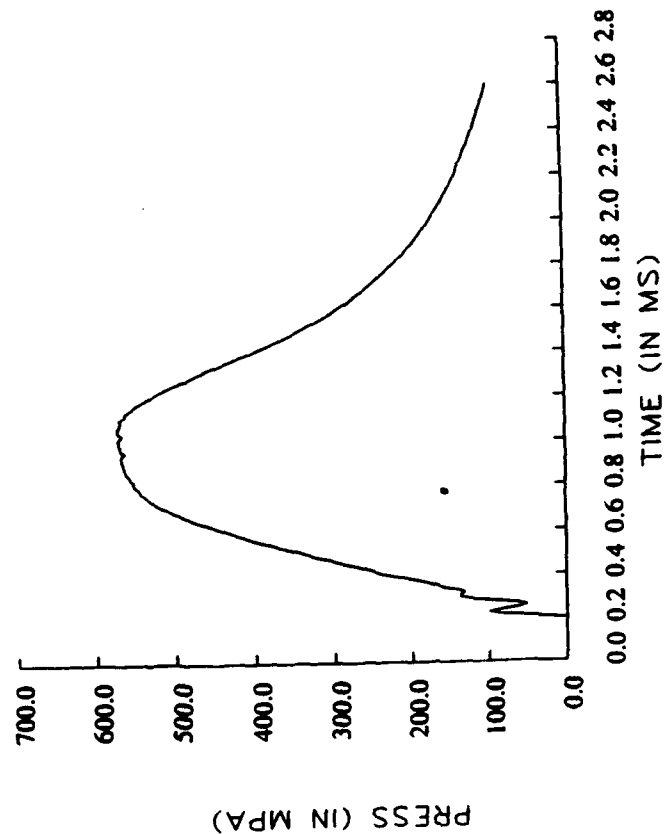
EXPERIMENTAL PRESSURE
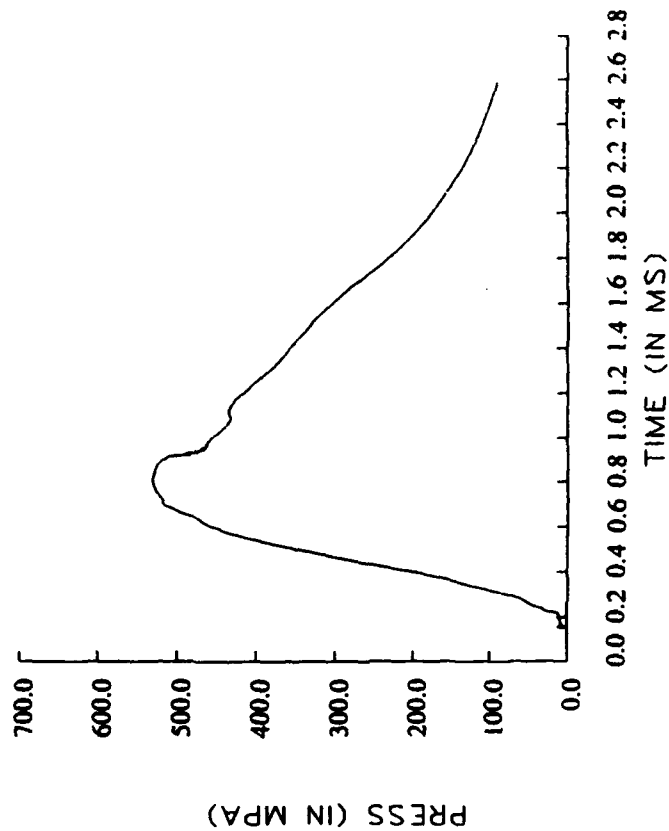
GDLS SHOT 45

PROJECTILE DYNAMICS vs TIME

EXPERIMENTAL EXIT VELOCITY AT 130.5 cm = 1170.0 m/s

NUMERICAL EXIT VELOCITY AT 130.5 cm = 1183.75 m/s

DISPLACEMENT

VELOCITY

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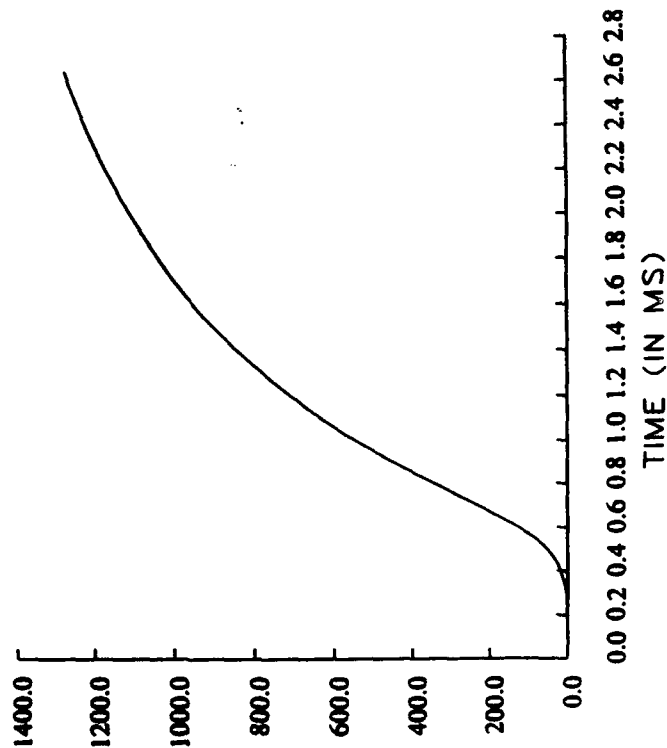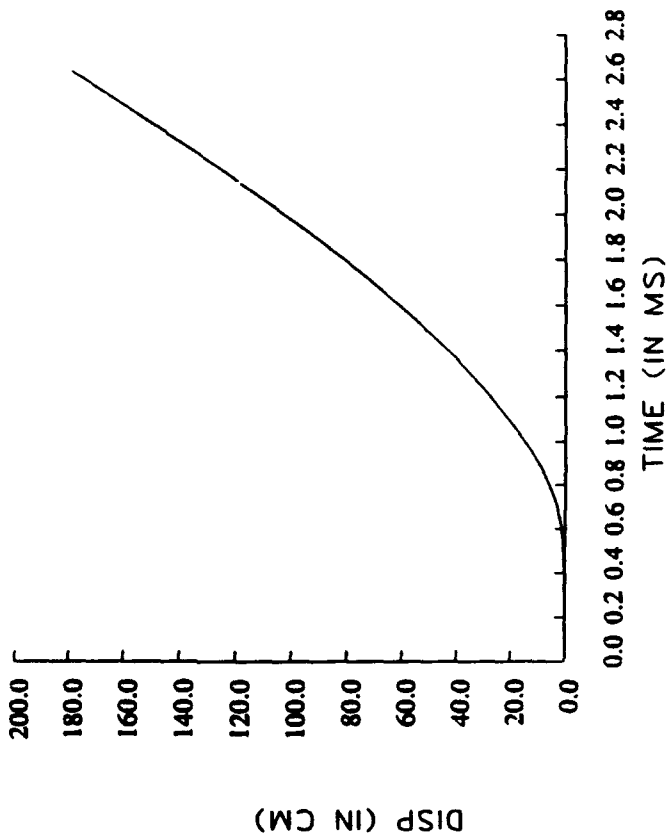
GDLS SHOT 122 INPUT DATA
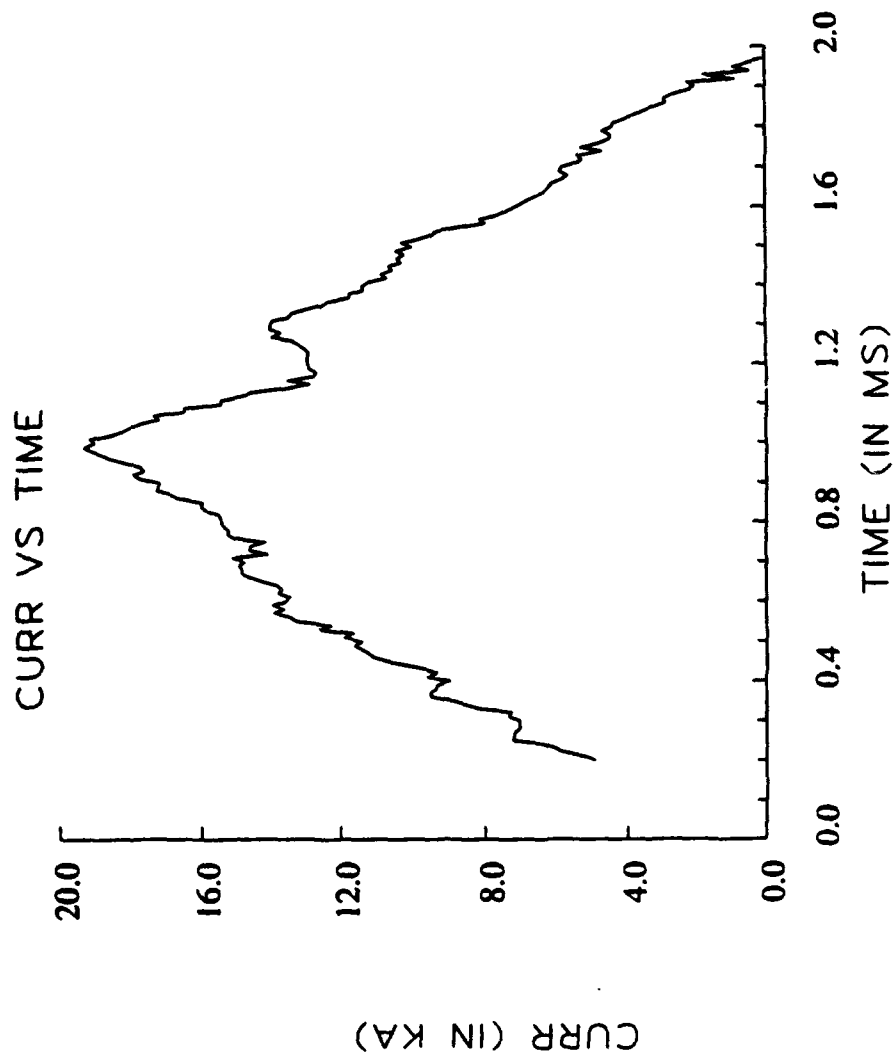
7 LAYER THERMOCHEMISTRY

| % of Radius | Flame Temperature (K) |
|---|---|
| | |

CURRENT HISTORY

CURR VS TIME
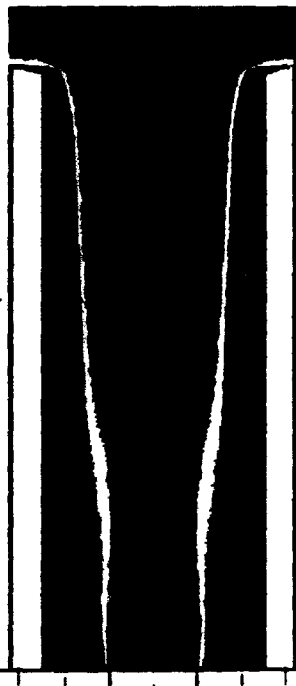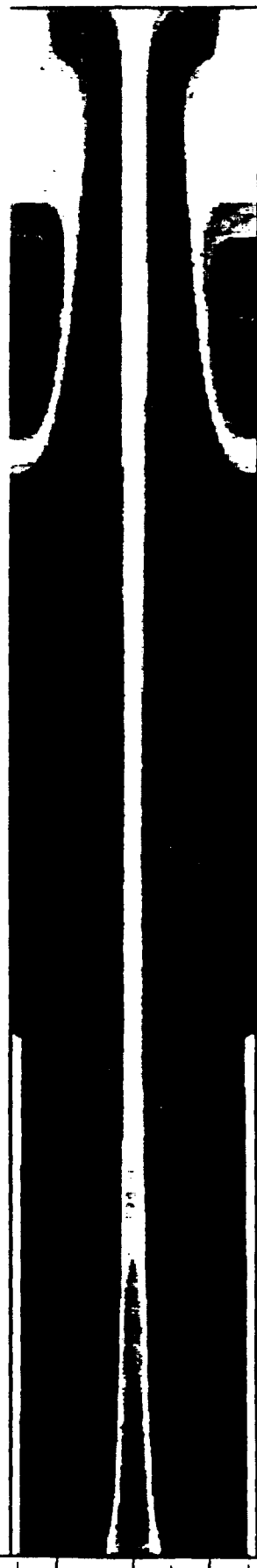
# GDLS SHOT 122

## PRESSURE HISTORY COMPARISON AT PORT 1

**COMPUTED PRESSURE**

NUMERICAL SIMULATION

**EXPERIMENTAL PRESSURE**
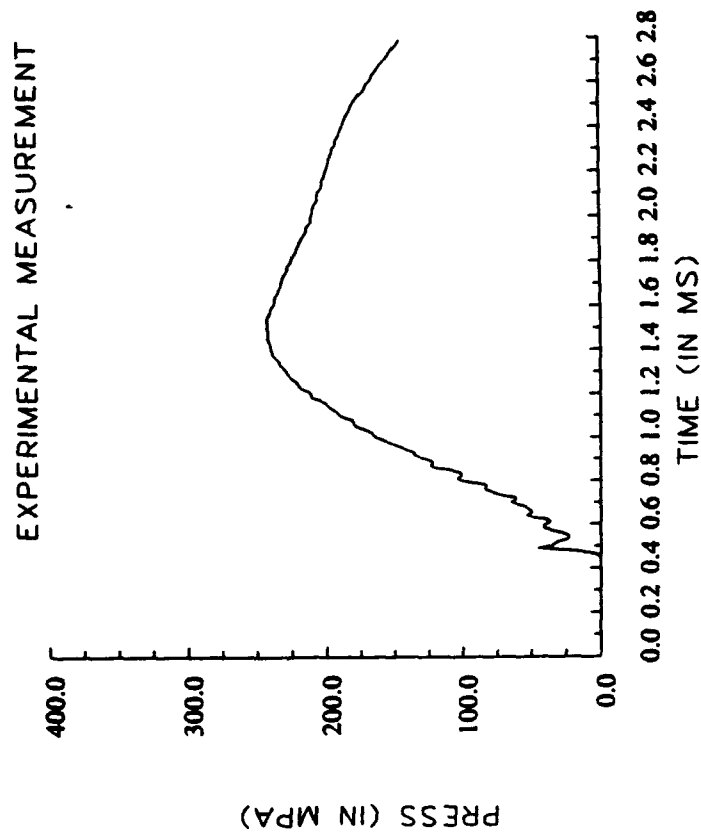
EXPERIMENTAL MEASUREMENT
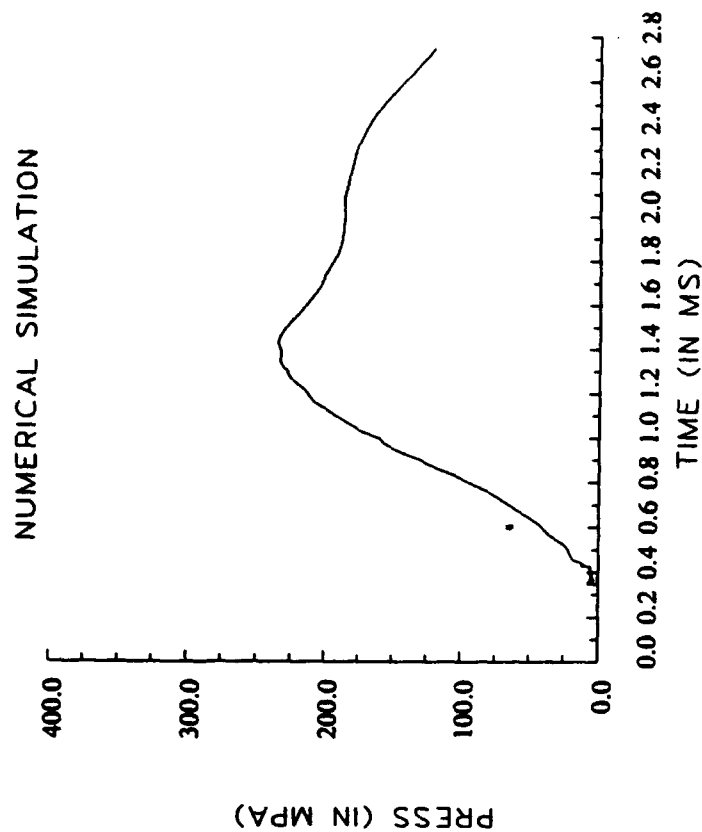
# GDLS SHOT 122

## PROJECTILE DYNAMICS vs TIME

EXPERIMENTAL EXIT VELOCITY AT 130.7 cm = 857 m/s

NUMERICAL EXIT VELOCITY AT 130.7 cm = 837 m/s

DISPLACEMENT

VELOCITY
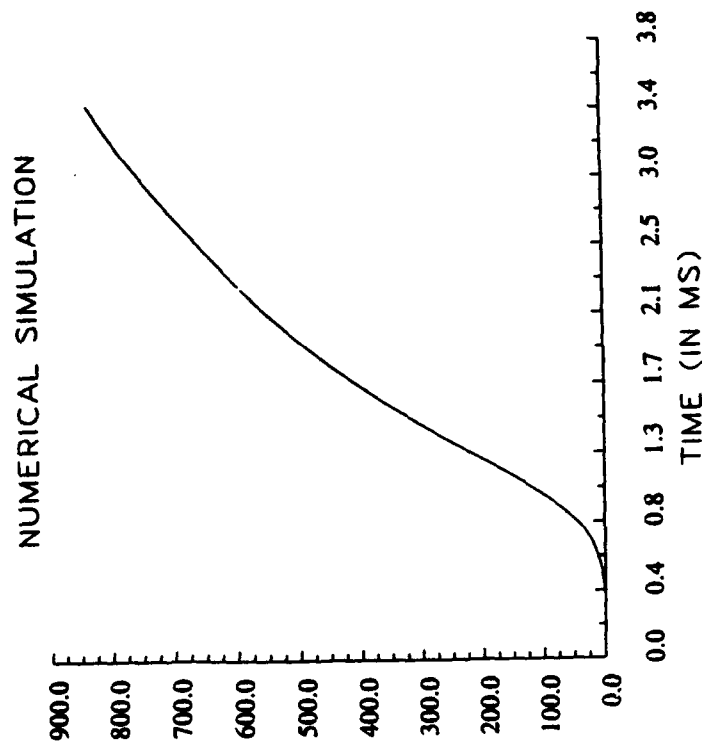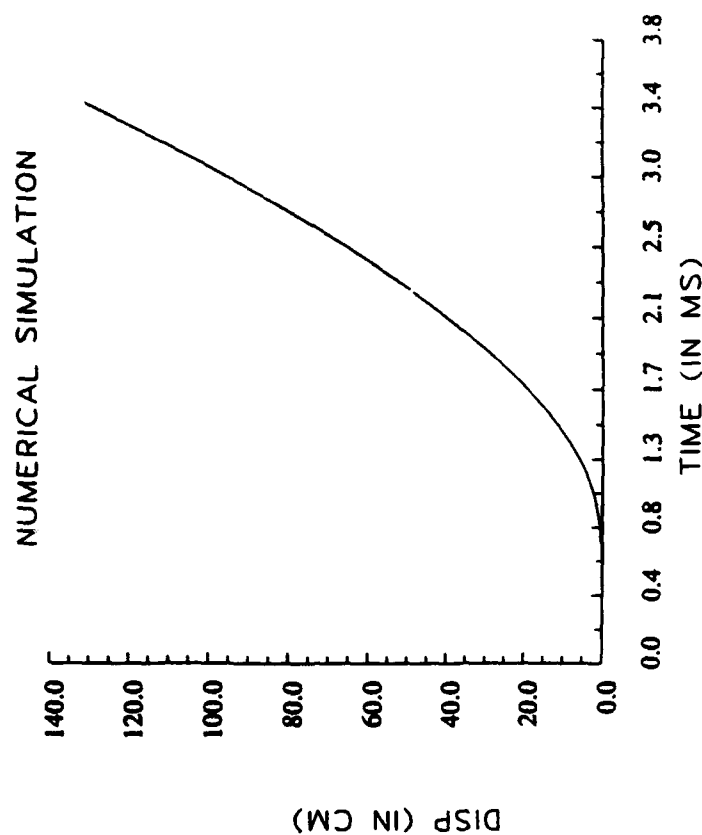
# FUTURE DIRECTION

## LP/ETC — PLASMA/WORKING FLUID INTERFACE

- DROPLET FORMATION/CONVECTION/COMBUSTION
- EULERIAN PARTICLE SOLVER OPERATIONAL IN CRAFT
- STRONG NONEQUILIBRIUM COUPLING
- VOLUMETRIC CONTRIBUTIONS

## SP/ETC — FLUIDIZED BED/PARTICLE EROSION

- PARTICLE CONVECTION/COMBUSTION
- LAGRANGIAN PARTICLE SOLVER OPERATIONAL IN CRAFT

INTENTIONALLY LEFT BLANK.

# Transient, Two-Dimensional Numerical Model of Plasma Behavior in an ETC Capillary

S. N. Kempka, M. W. Glass, D. A. Benson, D. W. Kuntz, G. F Homicz

Sandia National Laboratories

Fluid and Thermal Sciences Department

Albuquerque, NM

Sandia National Laboratories

# ETC Objectives/Issues

- ETC Propulsion Objective: Initiate and control combustion with a plasma

  - use a strong, sustained plasma jet to avoid LP combustion instabilities
  - plasma flow provides significant mixing during combustion process
  - control combustion by electrically controlling plasma discharge

- Issue: Lack of repeatability

  - is plasma behaving as expected?

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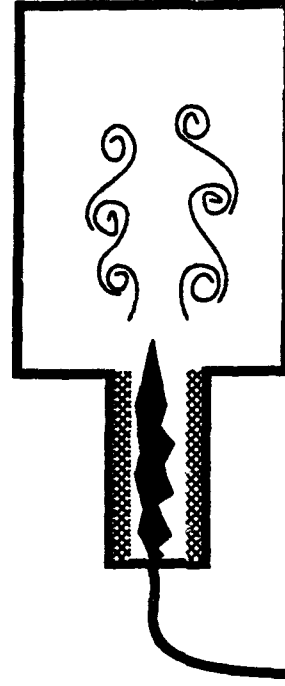
# Overview

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- **General Approach: Combined experimental and modelling effort**

  - non-combustion capillary discharge (SNL experiments)

- **Review of Plasma Phenomena**

- **Motivation for multi-dimensional, transient model**

- **Phenomenological models**

  - turbulence
  - ablation
  - thermal radiation
  - electrical power dissipation: electric field, electrical conductivity
  - plasma initiation

- **Demonstration calculation: simulation of SNL experiment ET038**

# Modelling Focus: Plasma Nonuniformities

Engineering Science Center

• Modeling Objective: Do plasmas behave as expected? (~ Isothermal?)

- Non-uniformity not unlikely in a positive feedback system:

  ohmic deposition increases with increasing temperature

- Evidence of plasma non-uniformities:

  throughput limit, repeatability problems, 1D model

• Importance of plasma behavior on ETC Performance:

- Power dissipation: controls plasma flow rate

- Scaling: relationship of small-scale data to large-scale performance

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# SNL Capillary Discharge Experiments

Engineering Sciences Center

Sandia National Laboratories

Mixing Chamber

Capillary
3.4 cm long
Radius 0.29 cm

Nitrogen

Plasma

Polyethylene liner

Electrical Input
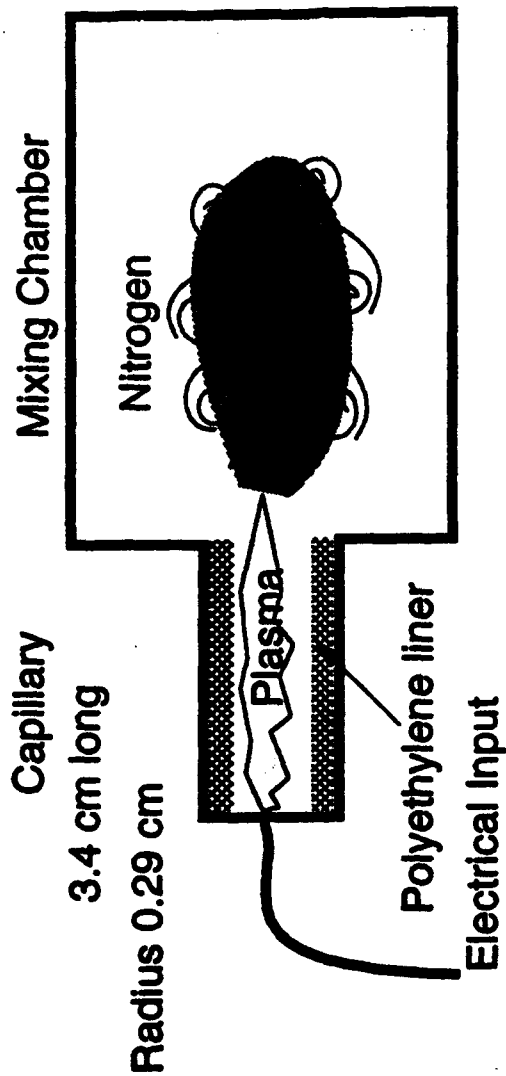
- pulsed power system charged to 4.0 kV, 3.2 kJ stored energy

- system pre-pressurized to 1000 psi, nitrogen - no propellant

- ablating polyethylene capillary liner

# Experimental Setup



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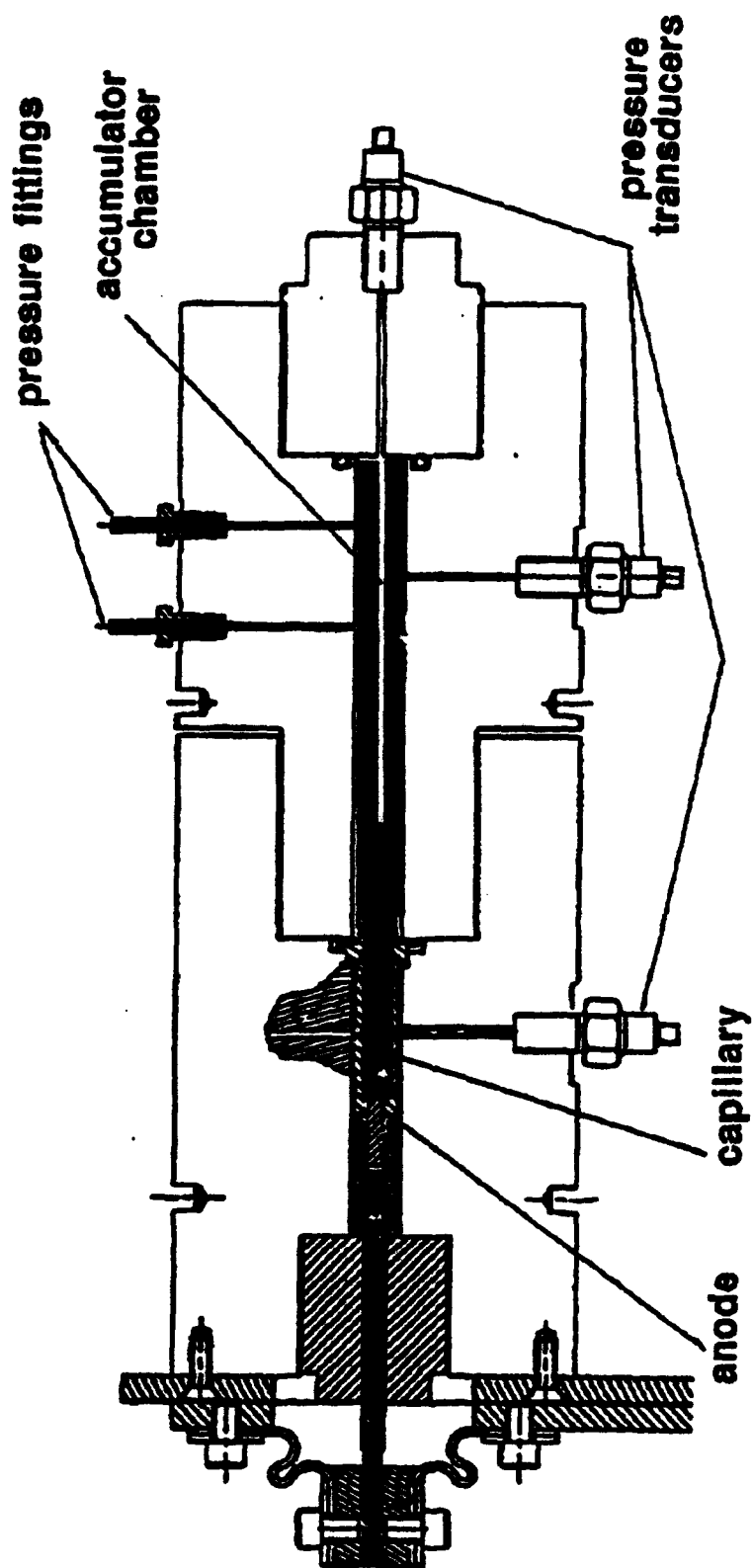
# Capillary Discharge Data

Engineering Sciences Center

Sandia National Laboratories

## Capillary Current and Voltage vs Time
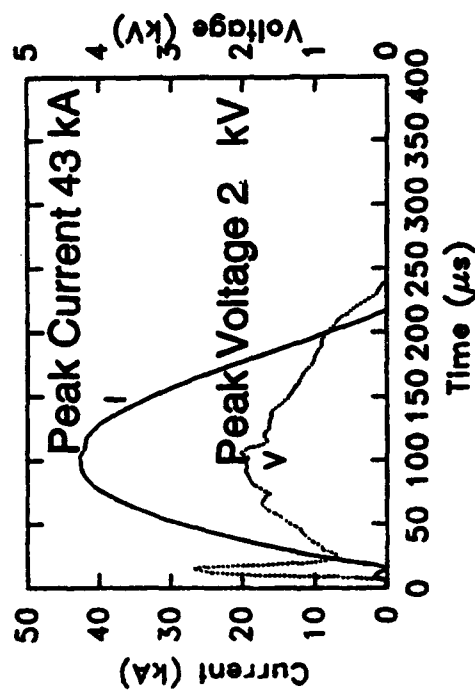


## Capillary Pressure vs Time
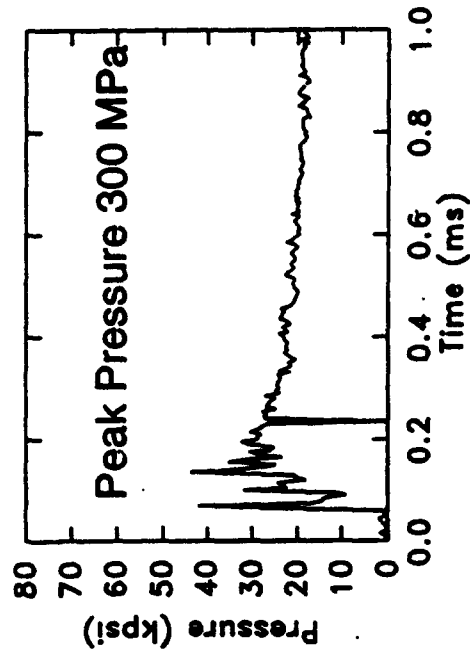


- Duration: ~ 200 µs, peak current occurs at 100 µs

- Mass of ablated polyethylene: 122 mg

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# Energy Transformation in an ETC Capillary
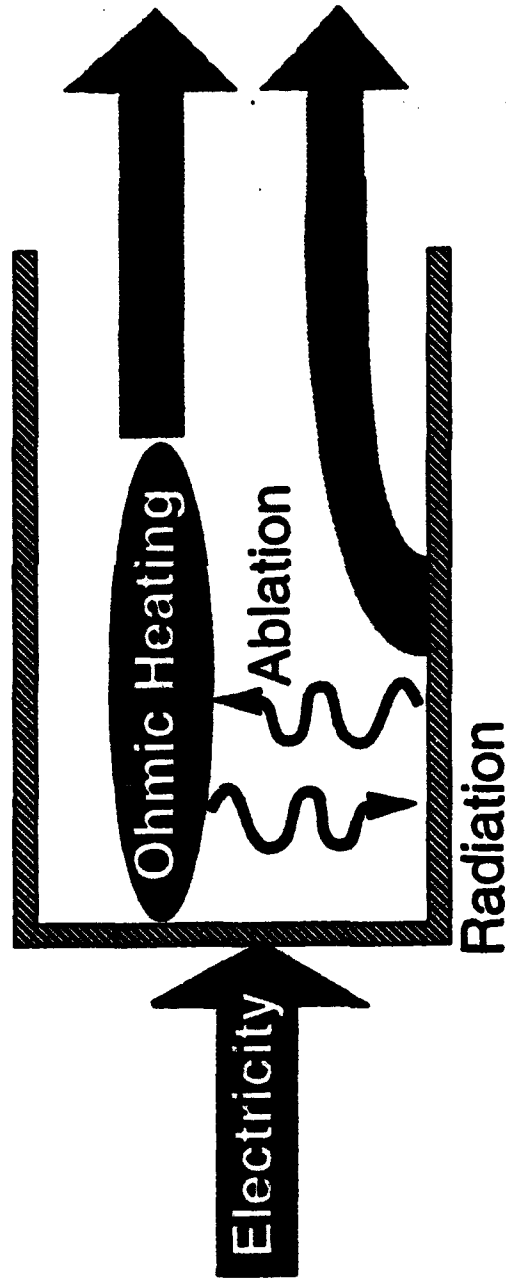


- Electrical energy in = convective flow out

# Motivation for 2D Transient Model

## • Why 2D?

- plasma flow from capillary into mixing chamber is 2D

  • 2D Hydrodynamic coupling between capillary and mixing chamber

- electric field and electric current could be 2D

## • Why transient?

- assess assumption of steady-state: does it exist?

- ablation rates are transient: only time-averaged rate data available

## • Reduce reliance on experimental data in simulations

- 1D models require Pressure, Electric Field, Current specifications

- developing 2D model to require only voltage data

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# Model Description

- Gas species, including dissociation and ionization
  - $C$, $C^+$, $C^{++}$, $H$, $H^+$, $N_2$, $N$, $N^+$
  - Saha equations for ionization
  - Lighthill dissociation model for nitrogen

- Conservation equations: compressible mass, momentum, energy

- Ohmic heating due to transient applied voltage difference
  - 2D Electric field based on transient voltage data
  - plasma electrical conductivity: Ion-electron, neutral-electron terms

- Radiative transport: Method of Discrete Ordinates
  - Zel'dovich and Raizer model for gas absorptance

- Ablation of polyethylene

- Ideal Gas Equation of State

# Governing Equations

• Mass Conservation for species I=C, H, N

$$\frac{\partial \rho_I}{\partial t} + \nabla \cdot (\rho_I \vec{u}) = 0$$

• Conservation of Momentum $\frac{\partial}{\partial t}(\rho u_j) + \nabla \cdot (\rho u_j \vec{u}) = -\nabla P$

• Conservation of Energy

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\rho \vec{u}(E + \frac{P}{\rho})) = \xi^2 \sigma + \nabla \cdot q_r$$

Ohmic Heating
(Electric Field)$^2$*Electrical Conductivity

Thermal
Radiation

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# Temperature Evaluation

Engineering Sciences Center

- Find temperature from energy values
  - Energy = thermal energy (ions, neutrals) + kinetic
  - All species, ions in a cell have the same temperature

$$\rho E = \rho |\vec{u}|^2/2 +$$

$$\sum_j \frac{3}{2} n_j kT \left(1 - (1 - \chi_{diss,j}) \Theta_{diss,j}\right) + n_j \chi_j^+ \left(\frac{3}{2} kT + I_j^+\right)$$

$$n_j \chi_j^{++} \left(3kT + I_j^+ + I_j^{++}\right), \, n_j \, -$$

$n_j$ number density, $\chi_j^+$ - ionization fraction, $I_j^+$ - ionization energy

$n_j \chi_j^{++}$ - ionization energy

# Ablation

**Boundary of Numerical Domain**

C, H

**Polyethylene CH₂**

- Glass phase transformations
- Spalling, particles
- Intermediate species
- Non-constant heats of vaporization and dissociation
- Non-thermodynamic equilibrium
- Spectral radiative transport
- kinetic energy of ablated material significant
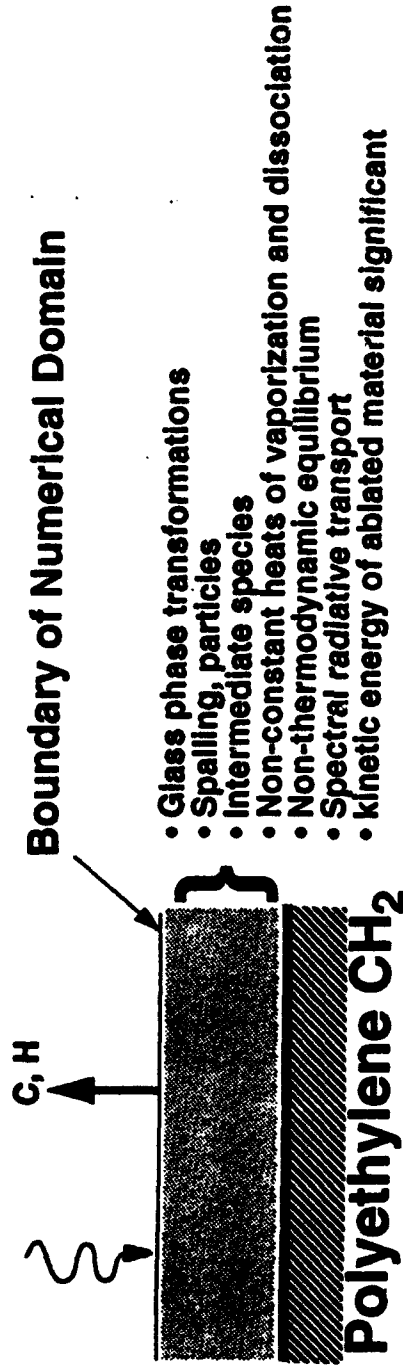
- Idealization of ablation

equilibrium energy balance: incident radiation = ablative enthalphy flux

$$q''_{radiation} = \rho_D u \{ \frac{5}{2} RT_D + \frac{u^2}{2} + \gamma \}$$

- Assume dissociation temperature $T_D$, density $\rho_D$, latent heat $\gamma$
- Solve cubic equation for u, given radiative flux

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# Ablation Model Features
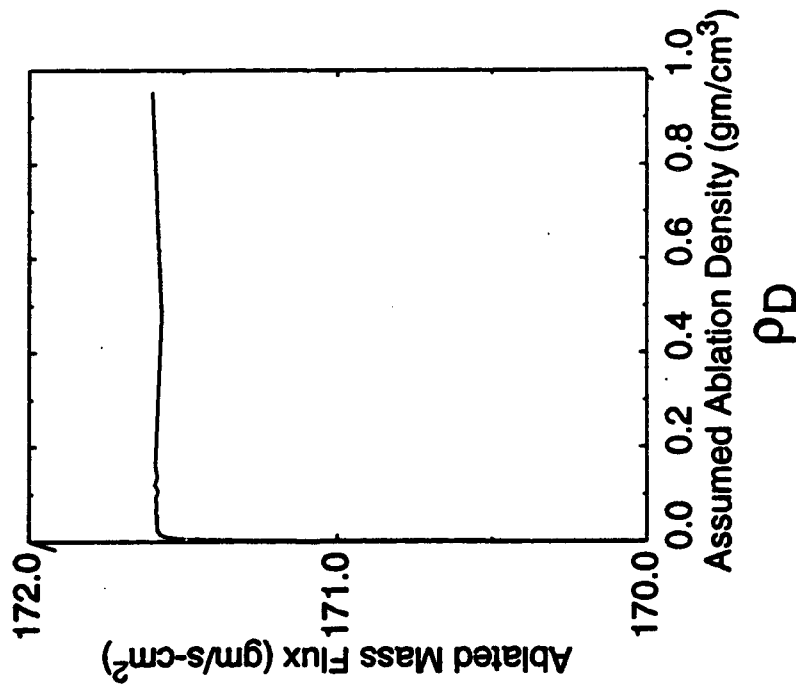
- Assume 4 eV blackbody heat flux

- Find that ablation mass flux is relatively insensitive to assumed polyethylene density

- Calculated ablation rate for ET038: 340 gm/s

- ET038 Ablation rate data (time-averaged) rate: 610 gm/s



Ablated Mass Flux (gm/s-cm$^2$) vs. Assumed Ablation Density (gm/cm$^3$) $\rho_D$

# Turbulence in ETC Capillaries

Engineering Sciences Center

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- Need to assess importance of turbulence

## Streamlines for Steady-State Flow

Fully Developed Section of Pipe
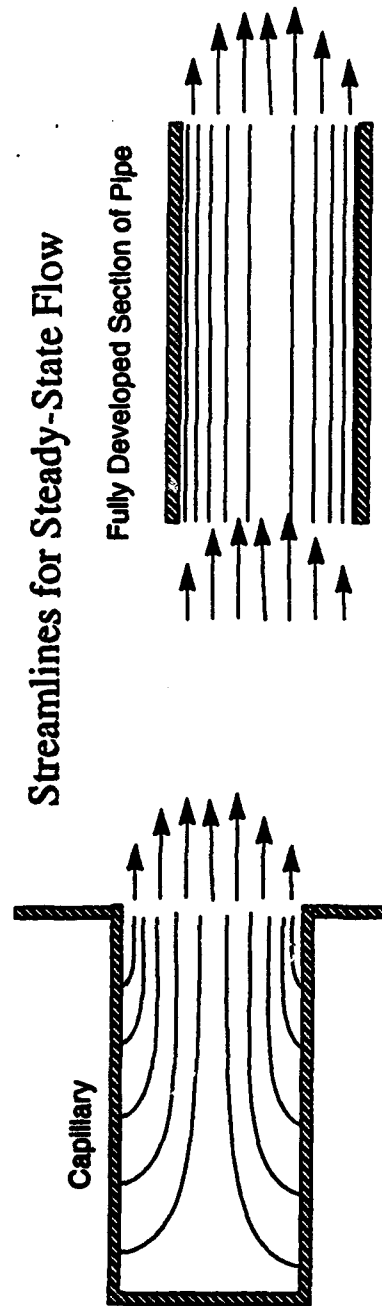
Capillary

- Compare capillaries to pipe flows
  - no flow at back wall, no development length - turbulence questionable
  - different boundary conditions (capillary wall blowing drives flow)
  - volumetric heat source
  - radiation

# Turbulence in ETC Capillaries, Cont'd

- Compare conductivities: fluid, turbulent, radiative

$$\rho C_p \frac{DT}{Dt} = \nabla \cdot [\,(k_{fluid} + k_{turbulence} + k_{radiation})\,\nabla T]$$

typically, $\quad k_{fluid} \ll k_{turbulence}$

- Compare $\quad k_{radiation} \quad$ and $\quad k_{turbulence}$

  - at 5 eV, $10^{22}$ cm$^{-3}$ (1D model: significant radial variations)

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# Turbulence in ETC Capillaries, Cont'd

- Turbulent conductivity (wall-generated turbulence)

  - $k_{turbulence} \approx \mu_{turbulence} C_p$ , $\mu_{turbulence} \approx O(10^2) \mu_{fluid}$

  - Spitzer formula for plasma viscosity

  $k_{turbulence} \approx 9 \cdot 10^3$ W/cm-eV

- Radiative conductivity: Zel'dovich and Raizer

  $k_{radiation} \approx 3 \cdot 10^6$ W/cm-eV

- Radiation dominates wall-generated turbulence for this example

  - radiation and turbulence are equivalent at 2 eV, where radial variations (due to radiation) are negligible

# Turbulence in ETC Capillaries, Cont'd
## Turbulent conductivity (wall-generated turbulence)

Engineering Science Center

- Turbulent conductivity (free-shear layer turbulence)

$$k_{turbulence} \approx 9 \cdot 10^5 \quad W/cm\text{-}eV$$

- Radiative conductivity: Zel'dovich and Raizer

$$k_{radiation} \approx 3 \cdot 10^6 \quad W/cm\text{-}eV$$

- Radiation & free shear layer turbulent transport rates are similar

  - origin of free-shear layer turbulence: baroclinic vorticity generation

  - turbulence models inappropriate for transitional flow

- Approach: use no turbulence model, examine solution fields for waves

# Electric Field Model

- Assume quasi-steady state

  - Zero divergence of current

$$\nabla \bullet (\sigma(T) \nabla V(t)) = 0$$

  - time t
  - temperature T
  - electrical conductivity $\sigma$
  - ohmic heating: $\sigma (\nabla V \cdot \nabla V)$

- Solver: Stabilized Error Vector Propagation (SEVP)



$dV/dx = 0$

$dV/dr = 0$

$dV/dx = 0$

$dV/dr = 0$

$V(t)$

$dV/dx = 0$

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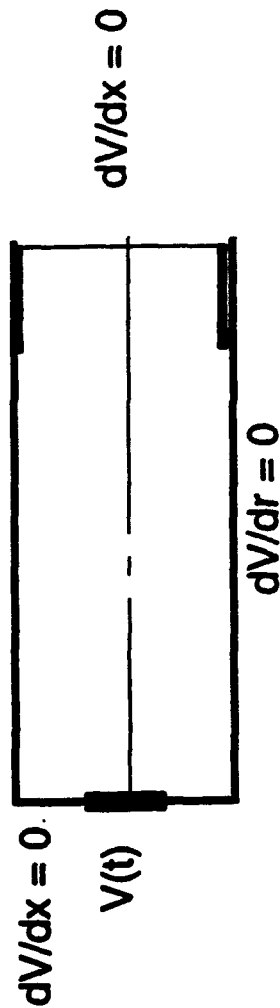
# Plasma Initiation

*Engineering Sciences Center*

**Santia National Laboratories**

Heated Gas

10 mil Fuse Wire
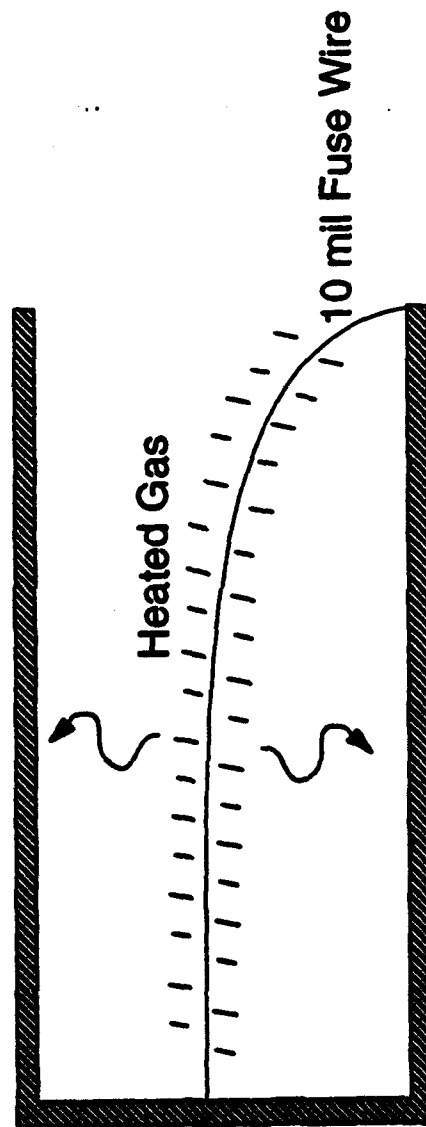
- Initially, all current carried by fuse wire

- At late times, ionized gas carries all the current

- How does this transition occur?

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# Uniform Power Deposition Calculation

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\rho \vec{u}(E + \frac{P}{\rho})) = \xi^2 \sigma + \nabla \cdot q_r$$

Thermal
Radiation

Ohmic Heating
(Electric Field)$^2$*Electrical Conductivity
**Replace with (Power data)/(Capillary Volume)**

- Calculate ohmic heating given voltage data

  - but don't use it, just compare with power data

- If ohmic heating agrees with power data:

  - Current will agree with data: power = voltage * current

  - Resistance will agree with data: power = voltage$^2$ /R

# Axisymmetric Model of Capillary and Mixing Chamber

Mixing Chamber

Capillary Radius 0.3 cm
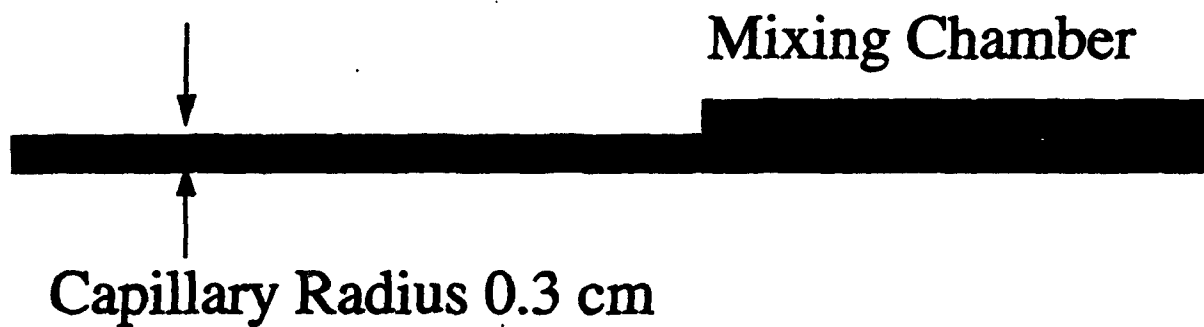
Overall Length 11.4 cm

Distorted Geometery
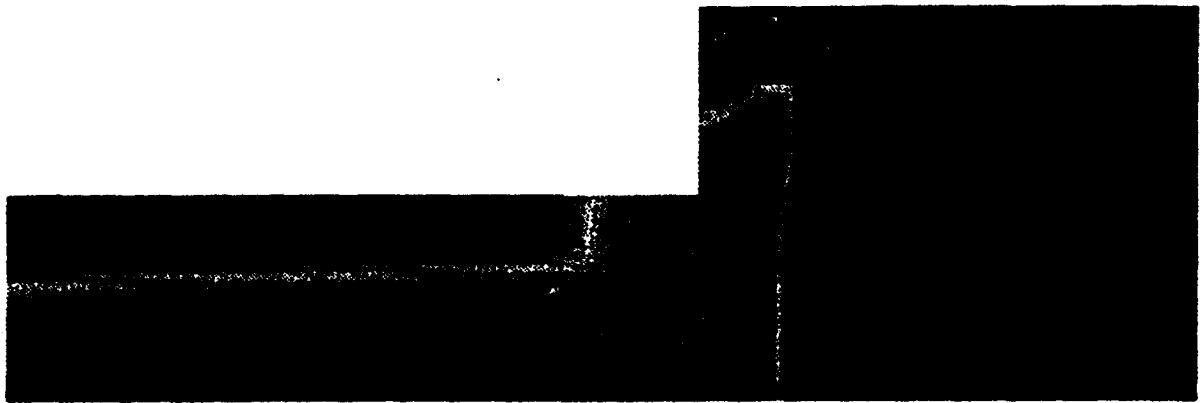
Cathode

Anode

Energy Deposition Region

## 100 μs

## Temperature (4.2 eV)

# 200 μs

## Temperature (3.3 eV)

100 μs

Pressure

200 μs

Pressure

100 μs

Polyethylene Density ($10^{-3}$)

200 µs

Polyethylene Density ($10^{-2}$)

Imposed Power (data)

Calculated Ohmic Heating

power

$10^8$

$10^6$

$10^4$

$10^2$

$10^0$

time

0.0  50.0  100.0  150.0  200.0
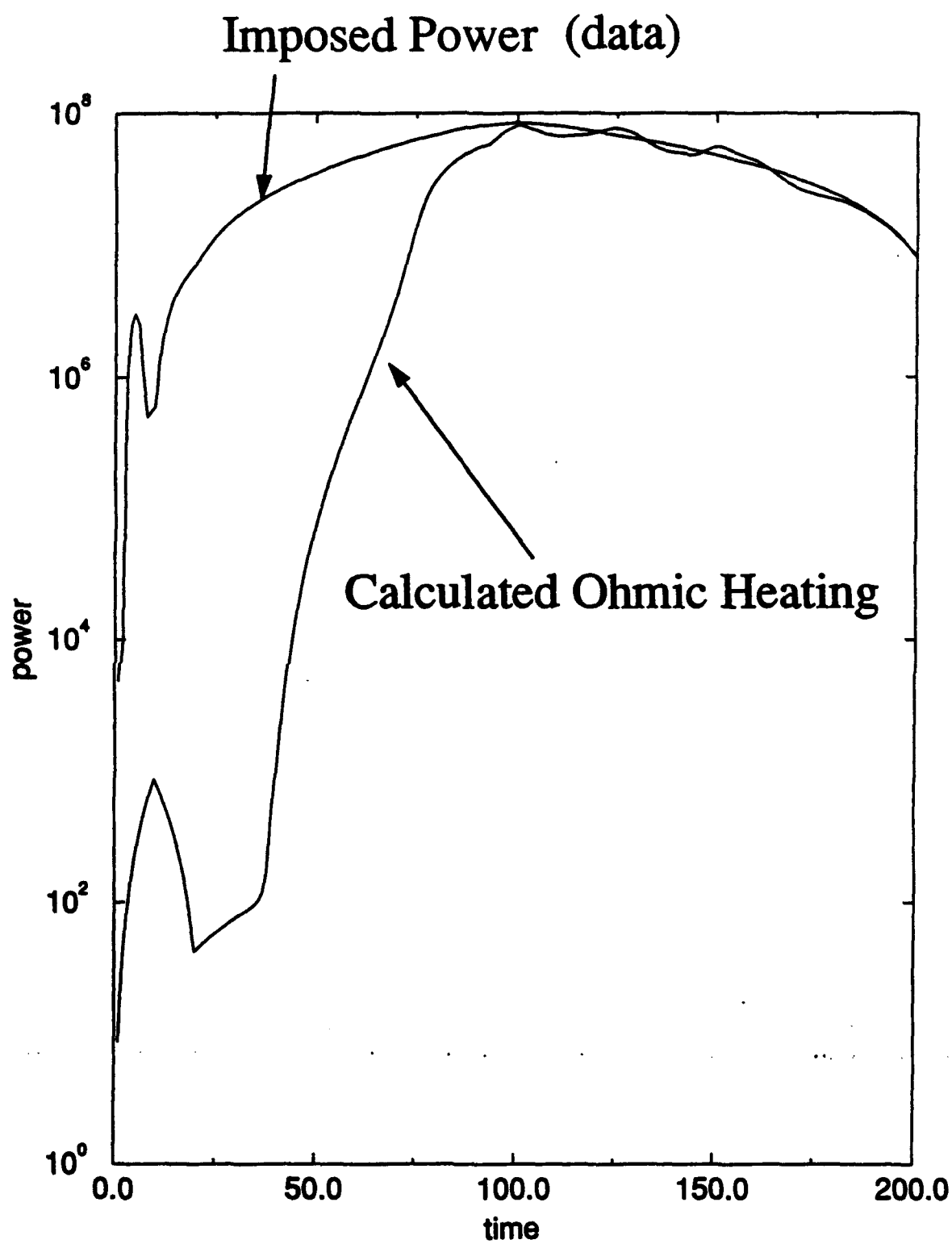
# Plasma Initiation, cont'd

Sandia National Laboratories

Centerline of Cartridge

- Radiative flux on polyethylene very small even if wire is initially hot

  - Ablated polyethylene is not an early participant

- Aluminum vaporizes, provides new electrical path

- Lee-More Model for aluminum electrical conductivity - progress

# Summary

Sandia National Laboratories

- Two-dimensional, transient model formulation

  - ohmic heating (voltage data, electrical conductivity -> voltage field)

  - discrete ordinate thermal radiation

  - ablation model

  - ionization, dissociation

- Uniform Power Deposition calculation (no fuse wire)

  - Transient pressure larger than data

  - Ohmic heating small at early times, good at later times

  - electrical conductivity too low at early-time

- Work in progress: include fuse wire vaporization

  - provides high electrical conductivity at early times

  - convected out of cartridge by late times

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Electric Armaments

FMC

# In-Bore Doppler Radar Measurements Of Projectile Kinematics

Workshop on ETC Modeling
Army Research Laboratory
Aberdeen, Maryland
May 12 - 13, 1993

Patrick Janke, Senior Engineer
Jahn Dyvik, Staff Engineer
Advanced Armaments
FMC Naval Systems Division
Minneapolis, Minnesota
U.S.A.

**Electric Armaments**

FMC

# OUTLINE

- **Automated Data Acquisition, Transfer and Reduction**

- **In-Bore Radar Measurements of Projectile Kinematics**

- **Development of an Inverse Ballistic Model**

- **Conclusions**

Electric Armaments

FMC

Automated Data Acquisition, Transfer, and Reduction

**Electric Armaments**

# FMC

# Data Acquisition System

| Data Display and Transfer | Data Display & Recording | Signal Conditioning | Sensors |
|---|---|---|---|

Fiber Optic Link

Modem

PC

Data Acquisition System

Oscilloscope

Amplifier

Amplifier

Amplifier

Laser

Laser

Radar

Pressure Transducers

Current Sensor

Voltage Sensor

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Jenke/ARL Proof/12/93/4
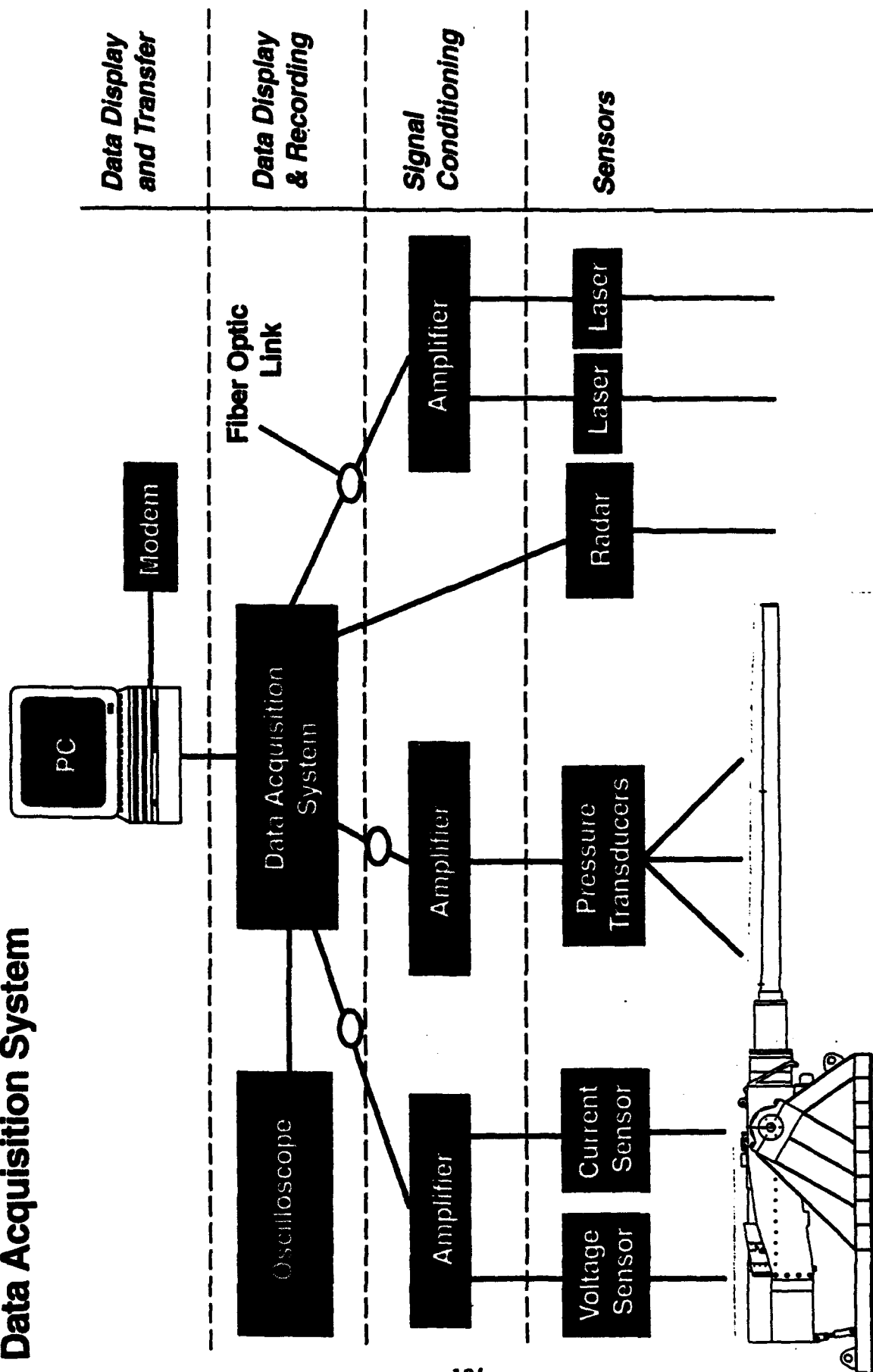
# Automated Data Transfer & Reduction

Electric Armaments

**FMC**

Pressure
Current
Voltage &
Radar Signals

PC

Modem

Modem

Vax

Pressure;
Electric Energy;
Position, Velocity
and Acceleration

Archival
Storage

Remote
Test Site

FMC
Minneapolis

Electric Armaments

FMC

In-Bore Radar Measurements of Projectile Kinematics

Electric Armaments

**FMC**
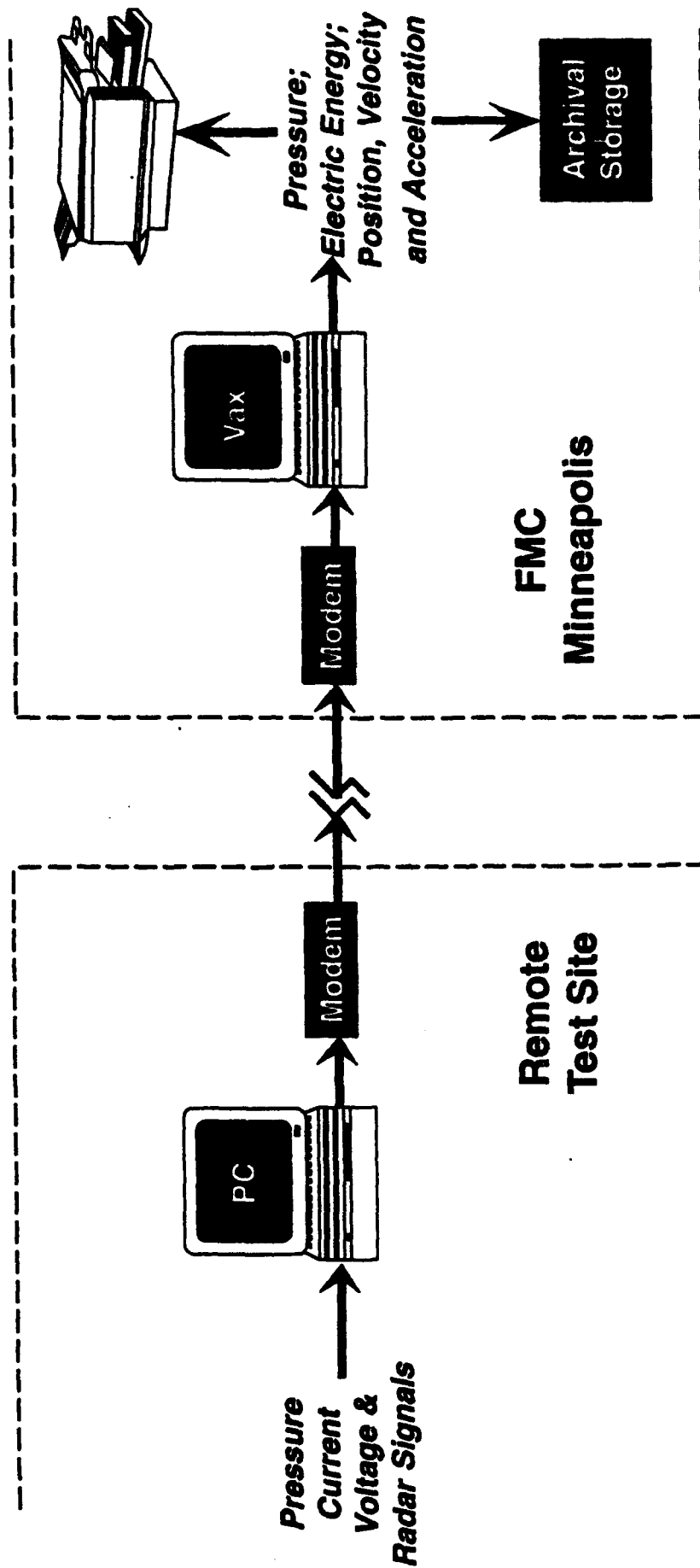
## Analysis of In-Bore Doppler Radar Data

**Doppler Signal**
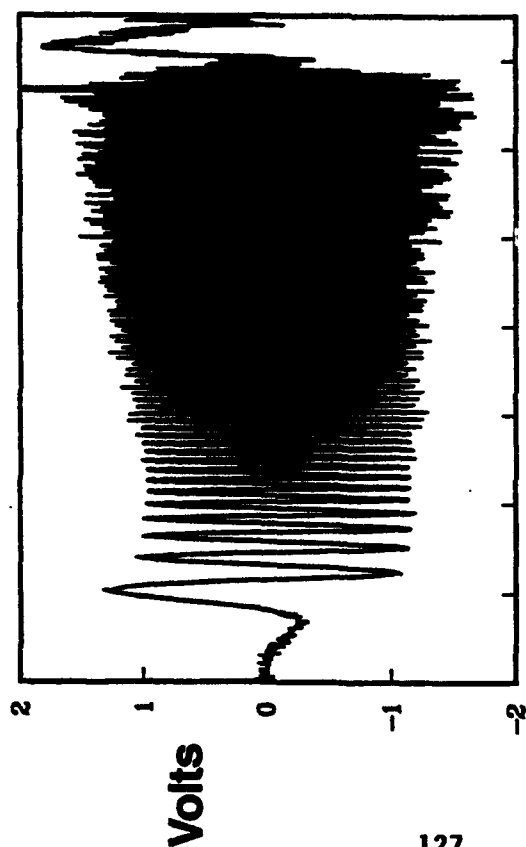
**Power Waterfall**

- *Separate into overlapping intervals*
- *FFT each interval*
- *High pass filter at muzzle exit*

Time

Time

Doppler Frequency

Volts

Janke/ARL Pres/5/12/93/7

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**Electric Armaments**

# Analysis of In-Bore Doppler Radar Data

**Power Waterfall**

Time
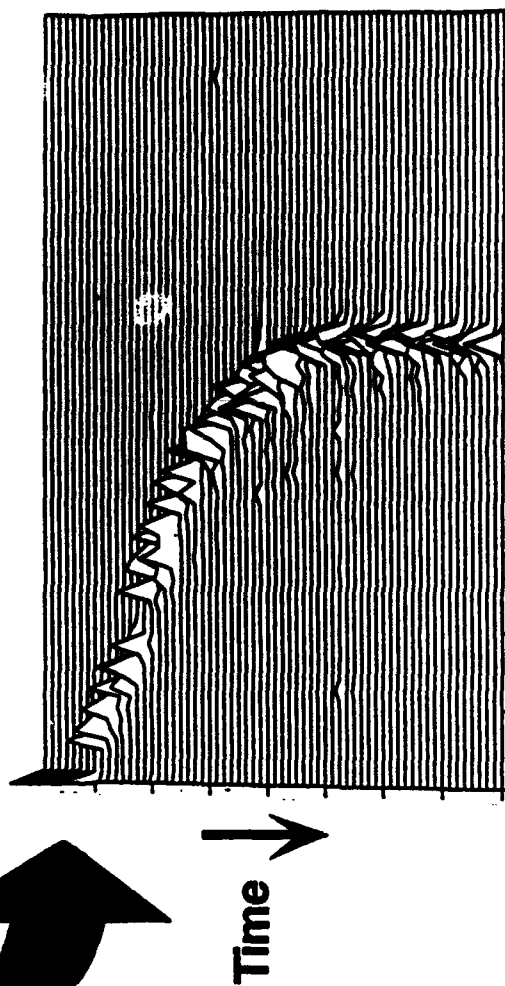
Doppler Frequency

**Projectile Velocity**

Velocity

Time
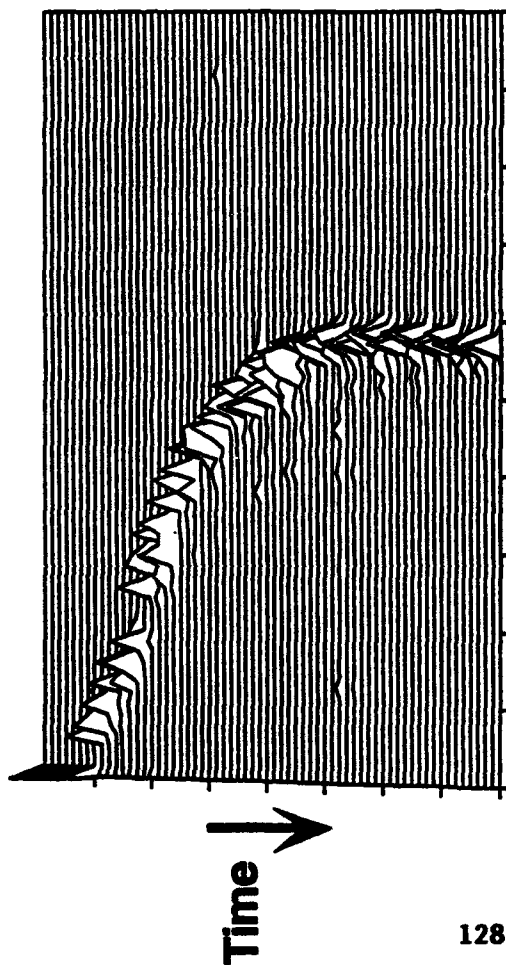
- Locate peak of power spectrum

- Remove data points with low SNR

- Convert Doppler frequency to projectile velocity
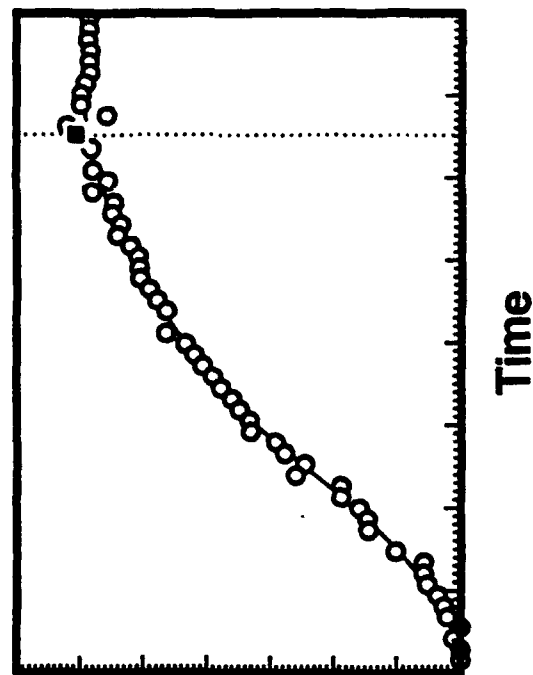
# Projectile Velocity

**Free Flight:**

$$V(t) = \frac{c}{1 + 2\left(\frac{f_o}{f_D(t)}\right)} \cong \frac{c f_D(t)}{2 f_o}; \quad \text{since} \left(\frac{V(t)}{c} << 1\right)$$

**In-Bore:**

$$V(t) = \left(\frac{c f_D(t)}{2 f_o}\right) \frac{1}{\sqrt{1 - \left(\frac{f_c}{f_D(t)}\right)^2}}; \quad f_c = \frac{0.293 c}{D/2}$$

$V(t)$ = Projectile Velocity    $f_c$ = Cutoff Frequency

$f_D(t)$ = Doppler Frequency    $c$ = Speed of Light

$f_o$    = Transmit Frequency    $D$ = Bore Diameter

129
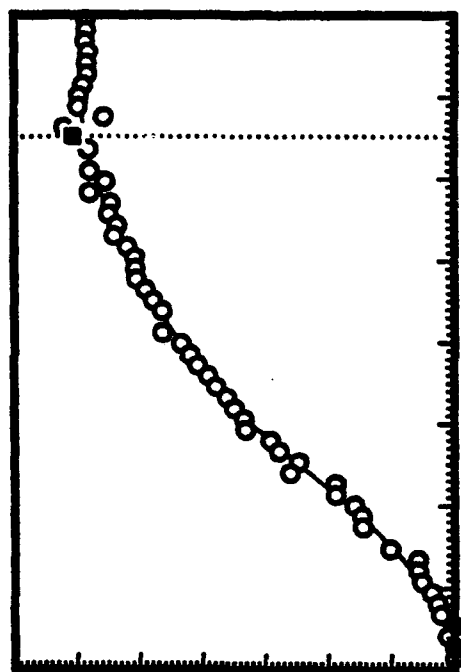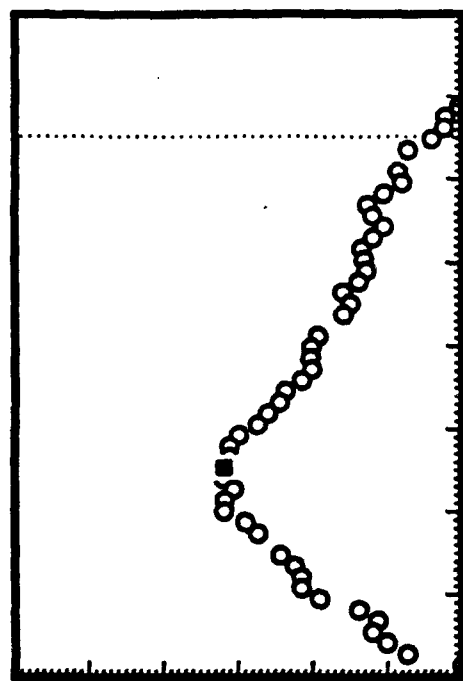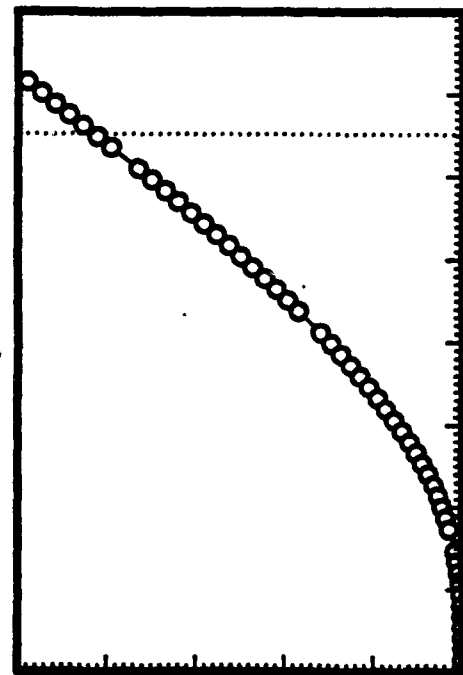
# Electric Armaments

**+FMC+**

# Muzzle Velocity

Velocity

Time
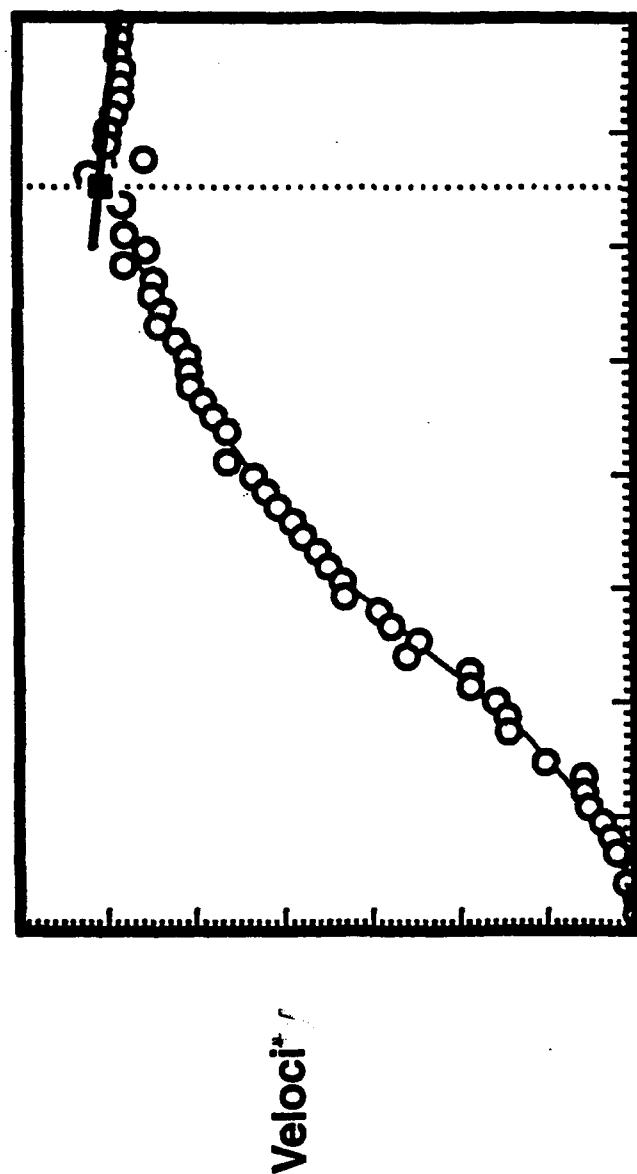
Straight line M.A.D. Fit of Free-Flight Values

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**Electric Armaments**

**FMC**

## Projectile Base Pressure

$$P_{base}(t) = \frac{ma(t) + F_{res}(t)}{A_b}$$

- ■ Measured
- ○ Calculated
- — Lagrange

**Travel**

**Base Pressure**

**Electric Armaments**

**FMC**

# Development of an Inverse Ballistic Model

**Electric Armaments**
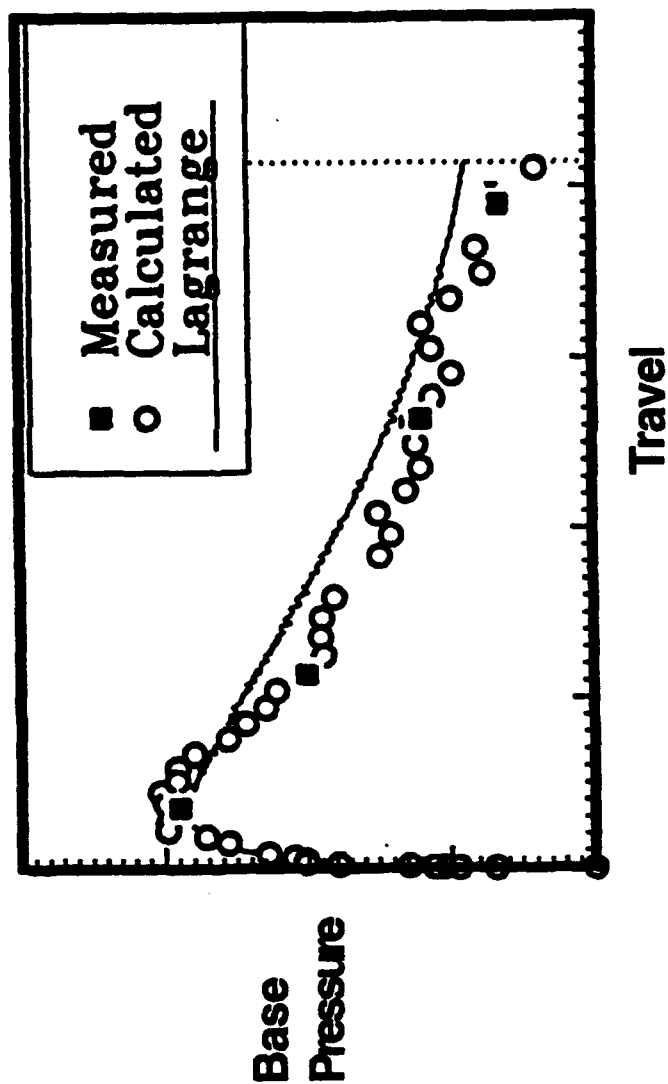
# Inverse Model - Formulation

## 1st Law Energy Balance:

*Electrical + Chemical = Work + Heat Loss*

$$E_{elec}(t) + cz(t)\left(\frac{I}{T_f(\gamma-1)}\right)(T_f - T(t)) = \left(\tfrac{1}{2}mV^2(t) + \tfrac{1}{6}cV^2(t)\right) + E_{heat}(t)$$

## Noble - Abel Equation of State:

$$\overline{P(t)}\left(V_c + X(t)A_b - \frac{c(1-z(t))}{\rho_s} - bcz(t)\right) = RT(t)\frac{cz(t)}{M}$$

**Electric Armaments**

# Inverse Model - Formulation

## Combine and Solve for Fraction Burned:

$$z(t) = \frac{\dfrac{V^2(t)}{2}\left(m + \dfrac{c}{3}\right) + \dfrac{\overline{P(t)}}{\gamma - 1}\left(V_c + X(t)A_b - \dfrac{c}{\rho_s}\right) + E_{heat}(t) - E_{elec}(t)}{\dfrac{c}{\gamma - 1}\left(I + \overline{P(t)}\left(b - \dfrac{1}{\rho_s}\right)\right)}$$

$E_{heat}(t)$ is calculated by modified Nordheim model.

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**Electric Armaments**

# Verification of Inverse Model
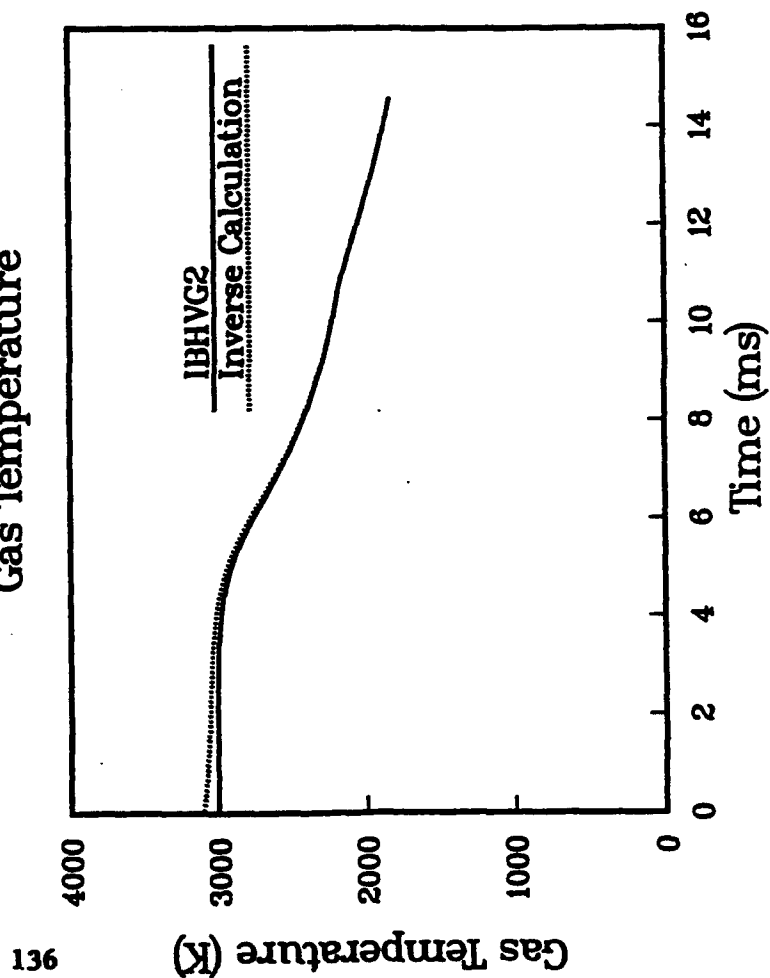
Fraction of Propellant Burned

Gas Temperature

Janke/ARL Pres/5/12/93/17

**Electric Armaments**
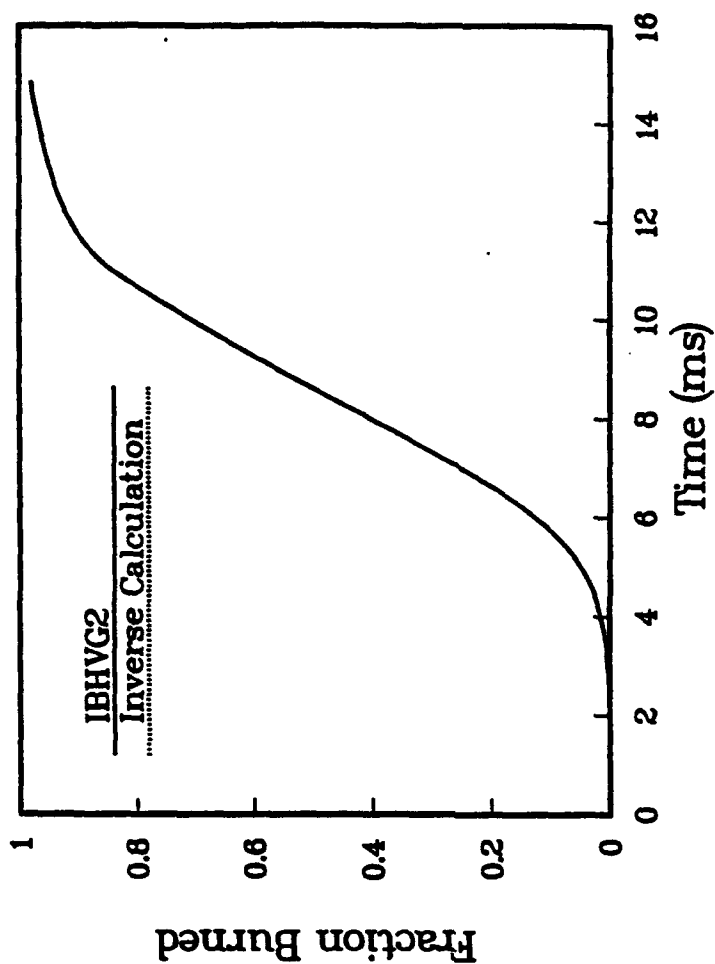
# Inverse Model - Solid Propellant Extensions

**Mass Burn Rate:**

$$\dot{m}(t) = c\,\frac{dz(t)}{dt}$$

**Linear Regression Rate:**

$$\dot{r}(t) = \frac{\dot{m}(t)}{\rho_s S(z)}; \quad S(z) = \text{Geometric Form Function}$$

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**Electric Armaments**

**FMC**
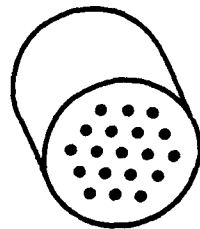
## Verification of Inverse Model

### Linear Regression Rate

IBHVG2
Inverse Calculation

Pressure (MPa)

Regression Rate (m/s)

### Propellant Surface Area

IBHVG2
Inverse Calculation

Time (ms)

Surface Area (m2)

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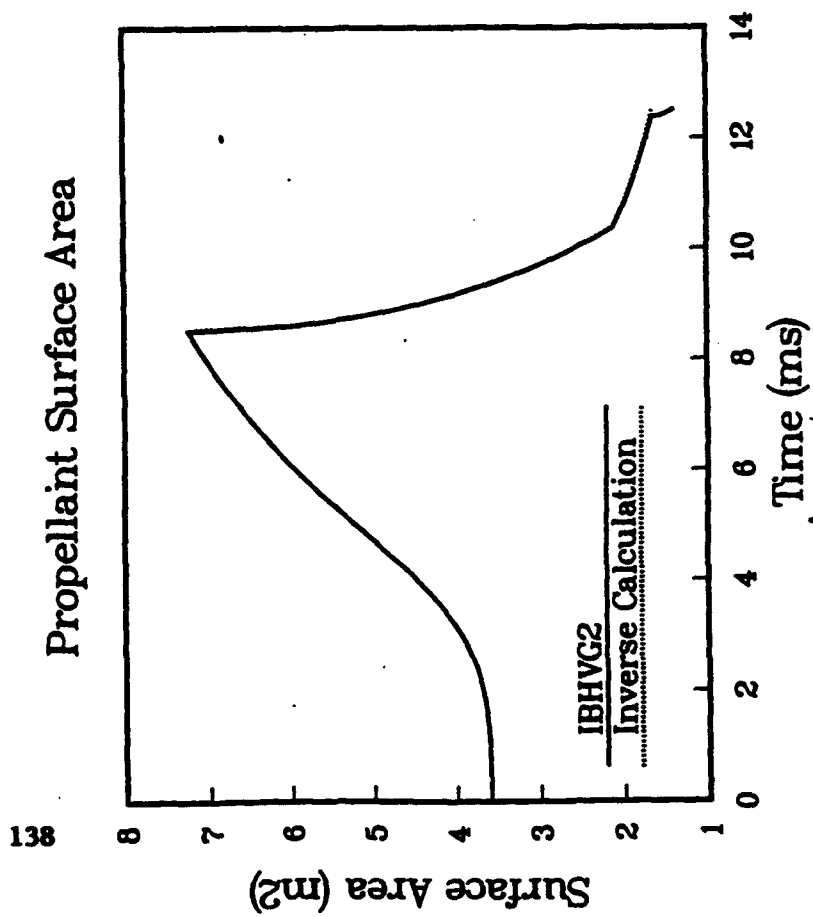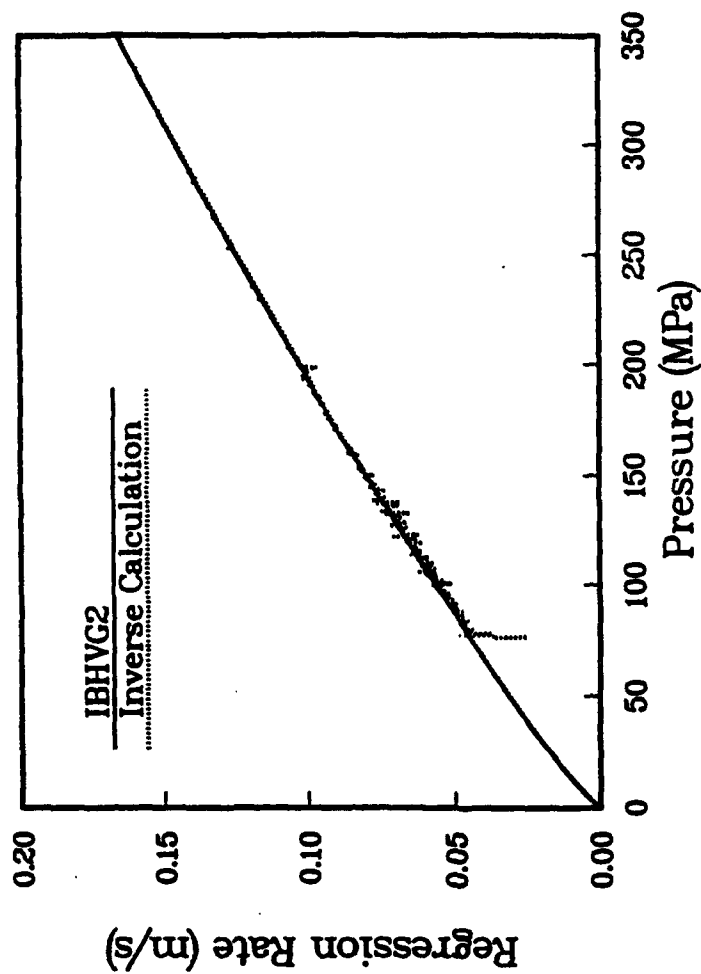
## Conclusions:

- Automated data transfer and reduction system provides fast, convenient access to shot results.

- Projectile travel is accurately measured using in-bore radar.

- In-bore radar provides a reasonable estimate of projectile acceleration and base pressure.

- Inverse analysis matches IBHVG2 results very well; model is ready for application to experimental data.

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Enhanced Propellant Burn Rate
through Plasma Erosion

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US Army Research, Development, and Engineering Center
Picatinny Arsenal, NJ
and
W.F. Oberle
US Army Research Laboratory
Aberdeen Proving Ground, MD
and
J.R. Greig
GT-Devices
Alexandria, Va
and
H.A. McElroy and J.G. Buzzett
Olin Ordnance
St. Petersburg, FL

## ABSTRACT

In both ETC gun firings and ETC closed bomb experiments to date, it has been observed that the burn rates of solid propellants are not altered by the presence of the ET plasma except through the pressure created by the addition of the electric energy. However, in a recent series of ET gun firings, we have observed that the burn rate of the propellant can be dramatically increased by the erosive effect of the plasma. The propellant was JA-2, and for these ETC gun firings the whole propellant charge was cast as a "single perf" monolithic grain. The central perforation was 0.25 inch diameter and the outside diameter of the grain was 1.10 inch. The propellant was fired in a 30mm (bore diameter) gun in the Army's ET Gun Facility at GT-Devices. The plasma generator was a high pressure capillary discharge and the emerging plasma was carefully injected into the central perforation in the propellant grain. All other surfaces of the propellant grain were inhibited using silicone grease. The charge design is described in detail, and results obtained by simulating these firings using IBHVG2 are discussed. From these simulations, it is concluded that the burn rate achieved in these gun firings was enhanced significantly through the erosive effect of the plasma.

# Enhanced Propellant Burn Rate Through Plasma Erosion

L. E. Harris, D. Chiu, J.Prezelski, P.O'Reilly, R. Marchak and
D. S. Downs

US Army Research, Development and Engineering Center
Picatinny Arsenal, NJ

W. F. Oberle

US Army Research Laboratory

Aberdeen, MD

J. R. Greig

GT Devices

Alexandria, Va

# OUTLINE

- **CBP Model**

- **System Requirements**
  - Tank
  - TMD

- **JA2 Monolith Gun Firings**
  - Experimental configuration
  - IBHVG2 Predictions
  - Pt traces and Residue
  - Inverse analysis

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# CBP EQUATIONS

$$Z_p = \frac{1}{\gamma}\left(\frac{l\,m}{P_{mean}\,A_b} - \frac{V_c - m\,\eta - V_{ab}}{A_b}\right) \tag{1}$$

$$Z_p = \frac{1}{2}\ddot{Z}_p\,t^2 \tag{2}$$

$$\dot{Z}_p = \frac{1}{2}\ddot{Z}\,t \tag{3}$$

$$m = \frac{Z_p\,\gamma A_b + V_c - C/\rho}{\frac{l}{P_{mean}} + \eta - \frac{1}{\rho}} \tag{4}$$

$$m = \frac{\frac{1}{2}\ddot{Z}_p\,t^2\,\gamma A_b + V_c - C/\rho}{\frac{l}{P_{mean}} + \eta - \frac{1}{\rho}} \tag{5}$$

$$\dot{m} = \frac{\ddot{Z}_p\,t\,\gamma A_b}{\frac{l}{P_{mean}} + \eta - \frac{1}{\rho}} \tag{6}$$

# CBP EQUATIONS

$$\bar{m} = \frac{\bar{Z}_p \gamma A_b}{\frac{1}{P_{mean}} + \eta - \frac{1}{\rho}} \tag{7}$$

$$m = \frac{1}{2} \bar{m} \, t^2 + m_0 \tag{8}$$

$$m_0 = \frac{V_c - C/\rho}{\frac{1}{P_{mean}} + \eta - \frac{1}{\rho}} \tag{9}$$

$$Z_p^{bo} = \frac{1}{\gamma} \left( \frac{IC}{P_{mean}^{bo} A_b} - \Lambda \right) \tag{10}$$

$$E_p^{sz} = E_p^{so} \left\{ 1 + \frac{1}{\gamma - 1} \left[ \frac{\bar{Z}_p^{bo}}{Z_p^{bo}} \right] \left[ 1 - \left( \frac{\bar{Z}_p^{bo}}{\bar{Z}_p^{sz}} \right)^{\gamma - 1} \right] \right\} \tag{11}$$

# CBP EQUATIONS

$$\dot{m} = \rho S \dot{r}$$ 

(12)

$$\dot{r}_p = \frac{\bar{m}}{2\pi l_c r_p \rho}$$

(13)

$$r_p = \left(\frac{\bar{m}t^2}{2\pi l_c \rho} + r_{p_i}^2\right)^{\frac{1}{2}}$$

(14)

## Table III  CBP Calculation of Interior Ballistics Time Profiles in a 120mm M256 Tank Gun

| t(MS) | $Z_p(M)$ | $V_p(M/S)$ | $T_m(K)$ | f(1) | $\dot{M}(KG/S)$ |
|---|---|---|---|---|---|
| 0.00 | 0.000 | 0· | 3,424 | 0.004 | 0 |
| 0.10 | 0.002 | 42 | 3,244 | 0.002 | 268 |
| 0.20 | 0.008 | 85 | 3,037 | 0.007 | 536 |
| 0.30 | 0.019 | 127 | 2,933 | 0.016 | 804 |
| 0.40 | 0.034 | 169 | 2,881 | 0.028 | 1,072 |
| 0.50 | 0.053 | 211· | 2,854 | 0.043 | 1,341 |
| 1.00 | 0.211 | 423 | 2,812 | 0.173 | 2,681 |
| 1.50 | 0.476 | 634 | 2,804 | 0.388 | 4,022 |
| 2.00 | 0.846 | 846 | 2,801 | 0.690 | 5,362 |
| 2.40 | 1.218 | 1,015 | 2,800 | 0.994 | 6,435 |
| 2.41 | 1.225 | 1,018 | 2,800 | 1.000 | 6,453 |
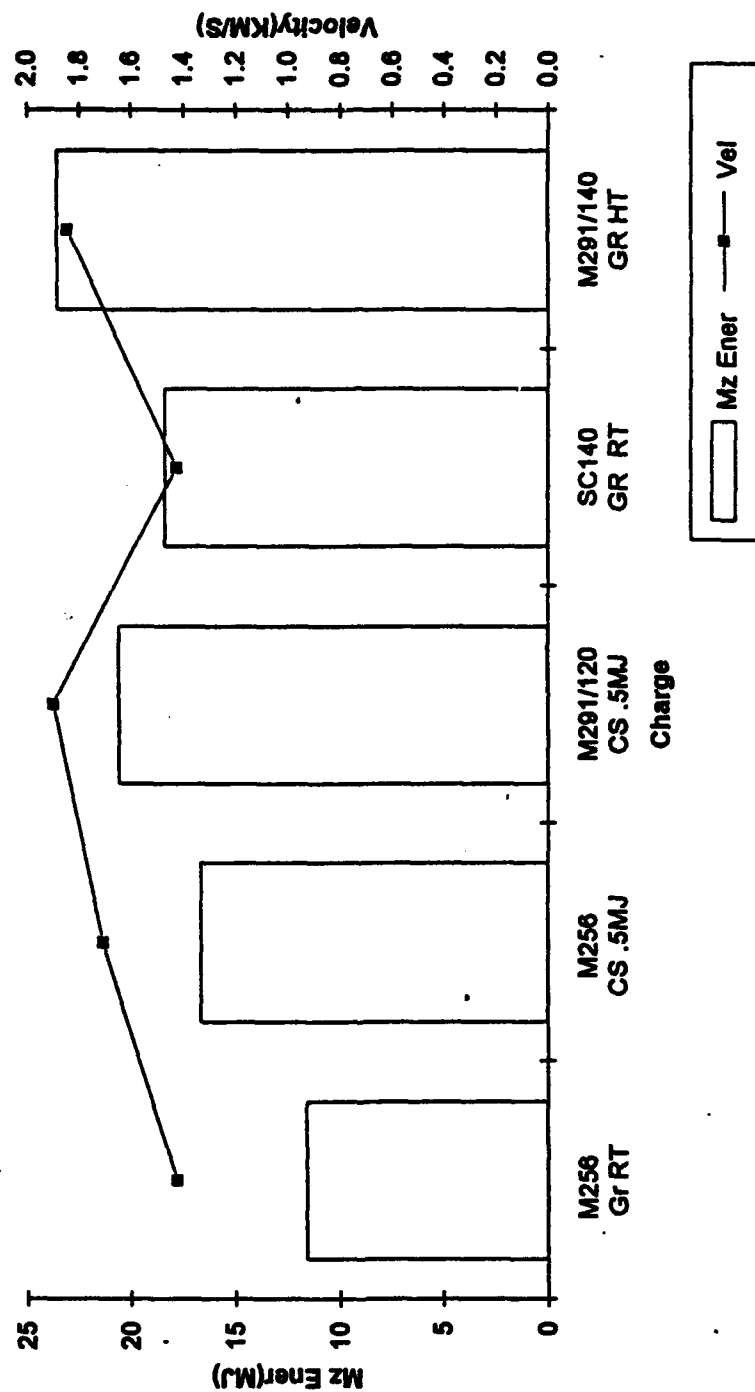
Figure 4. Projectile muzzle velocity versus velocity for 120- and 140-mm tank guns

Figure 6.  120-mm M291 ETC tank gun cartridge
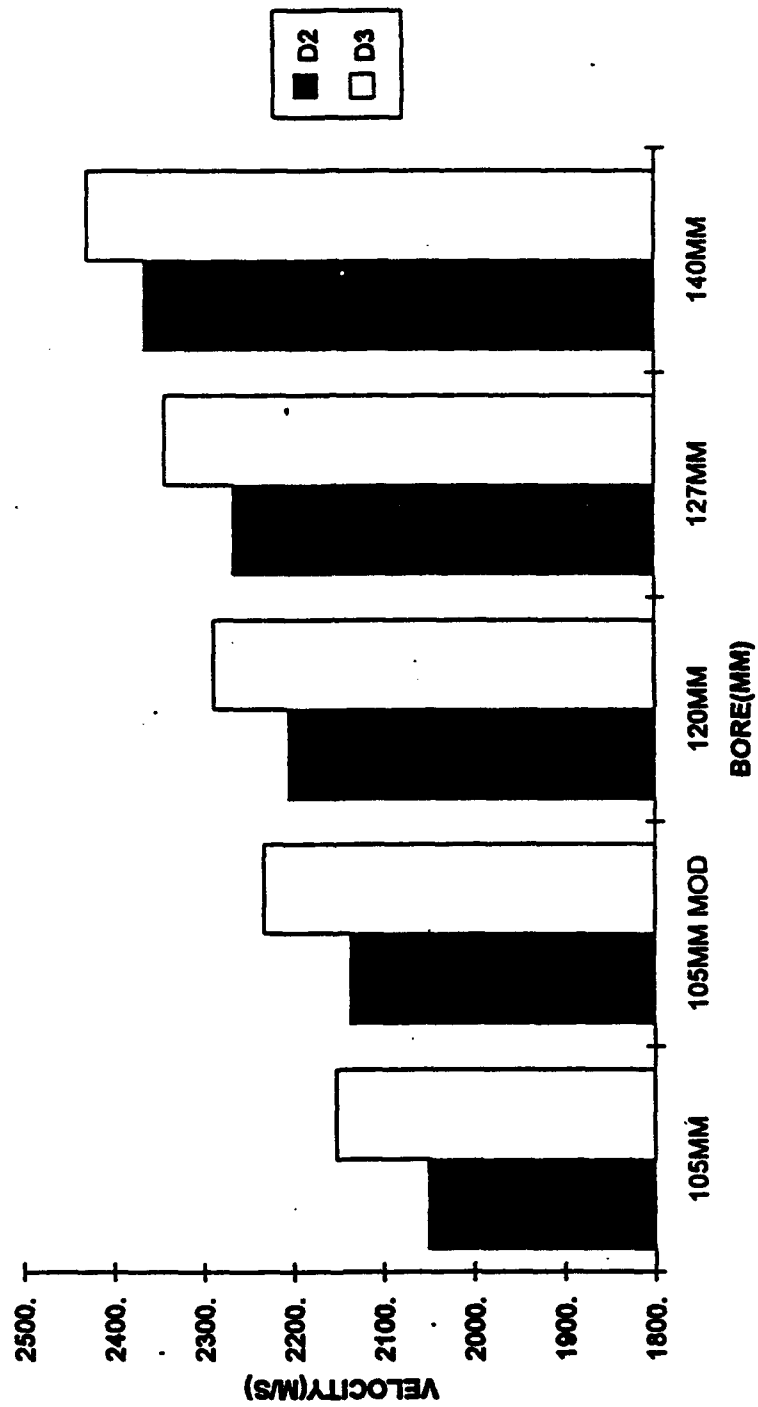
Figure 8. Muzzle velocity in various air defense guns
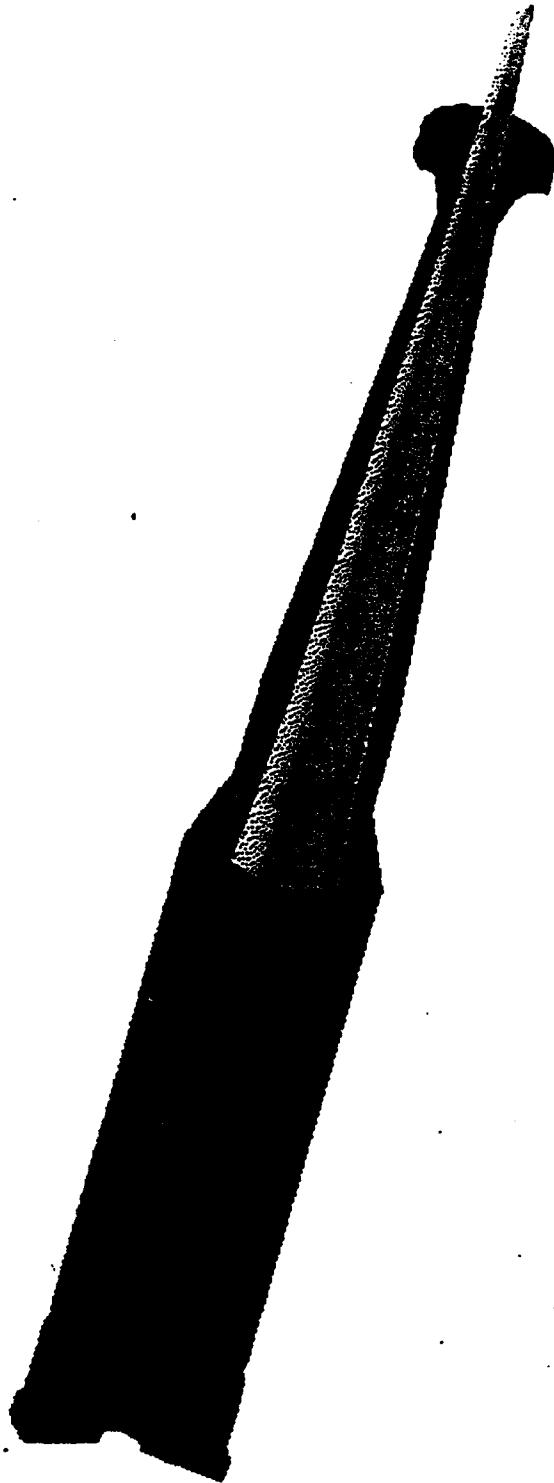
Figure 9.  105-mm ETC air defense cartridge
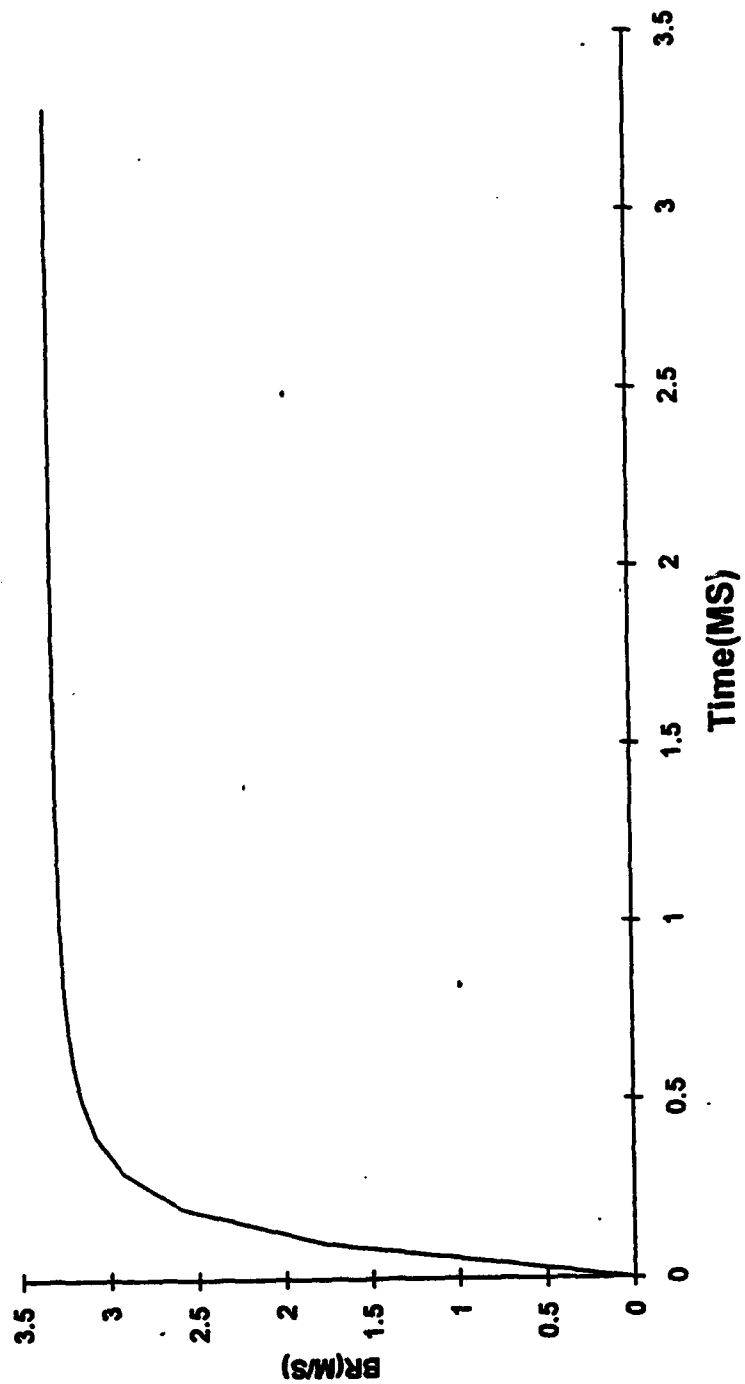
Figure 10. Propellant burning rate versus time for 120-mm M291 ETC cartridge

# Summary

- In the CBP model a 120mm M291 ETC gun using a cartridge with JA2 at a LD equal to its density with 0.5 MJ/KG EE attains a muzzle velocity of 1900 M/S that is slightly higher than a conventional 140mm M291 Tank Gun using granular JA2 at a LD of 1.

- CBP calculations indicate that a similar design for a 105mm ETC Air Defense gun will achieve velocities greater than 2 KM/s for both the D2 and D3 smart projectiles.

- If the mass generation rate required to meet the above performance is not achievement, plasma influenced grain de–consolidation at the correct rate would be required to meet performance.

PROJECTILE BASE

154

SHOT
START
RING
LOCATION

PROJECTILE
Wp=328.8gm

PROJECTILE
BASE
LOCATION

PC 1
GLOC = -6.5

PC 2
GLOC = -2.1

155
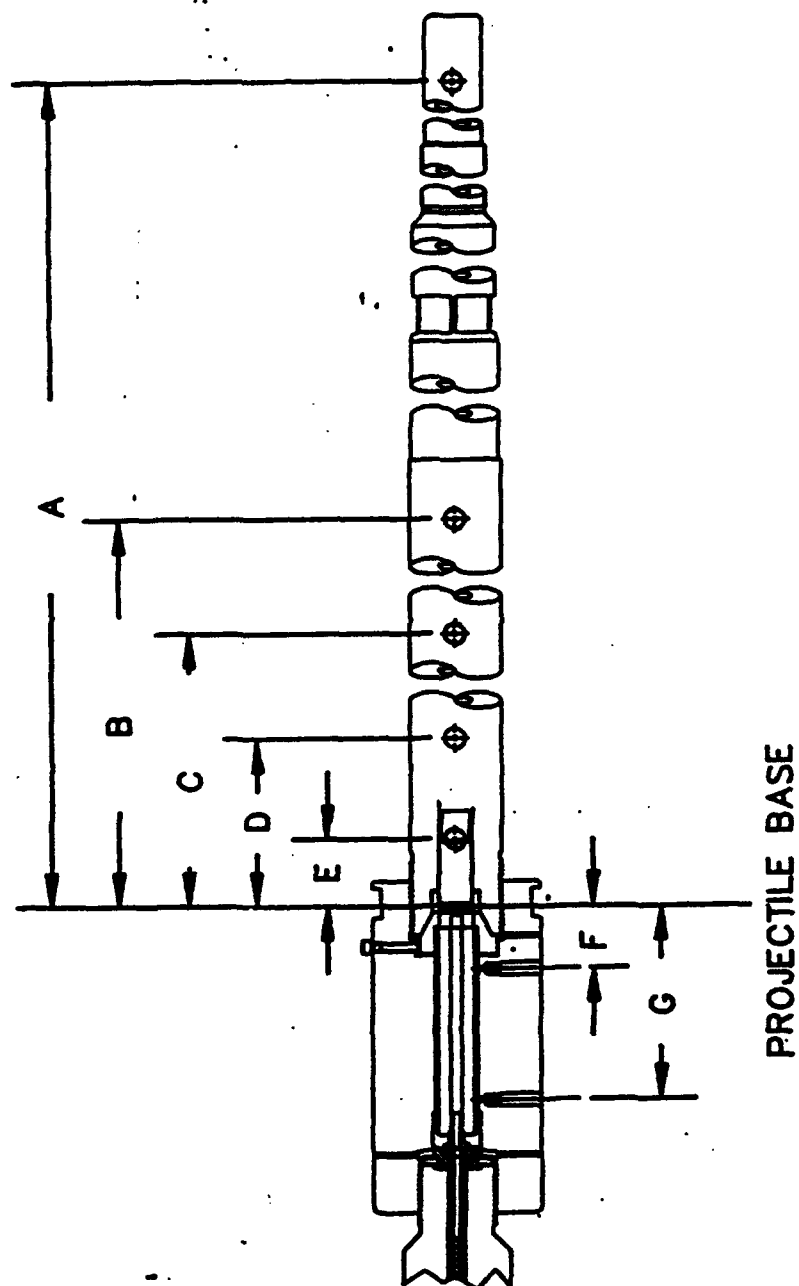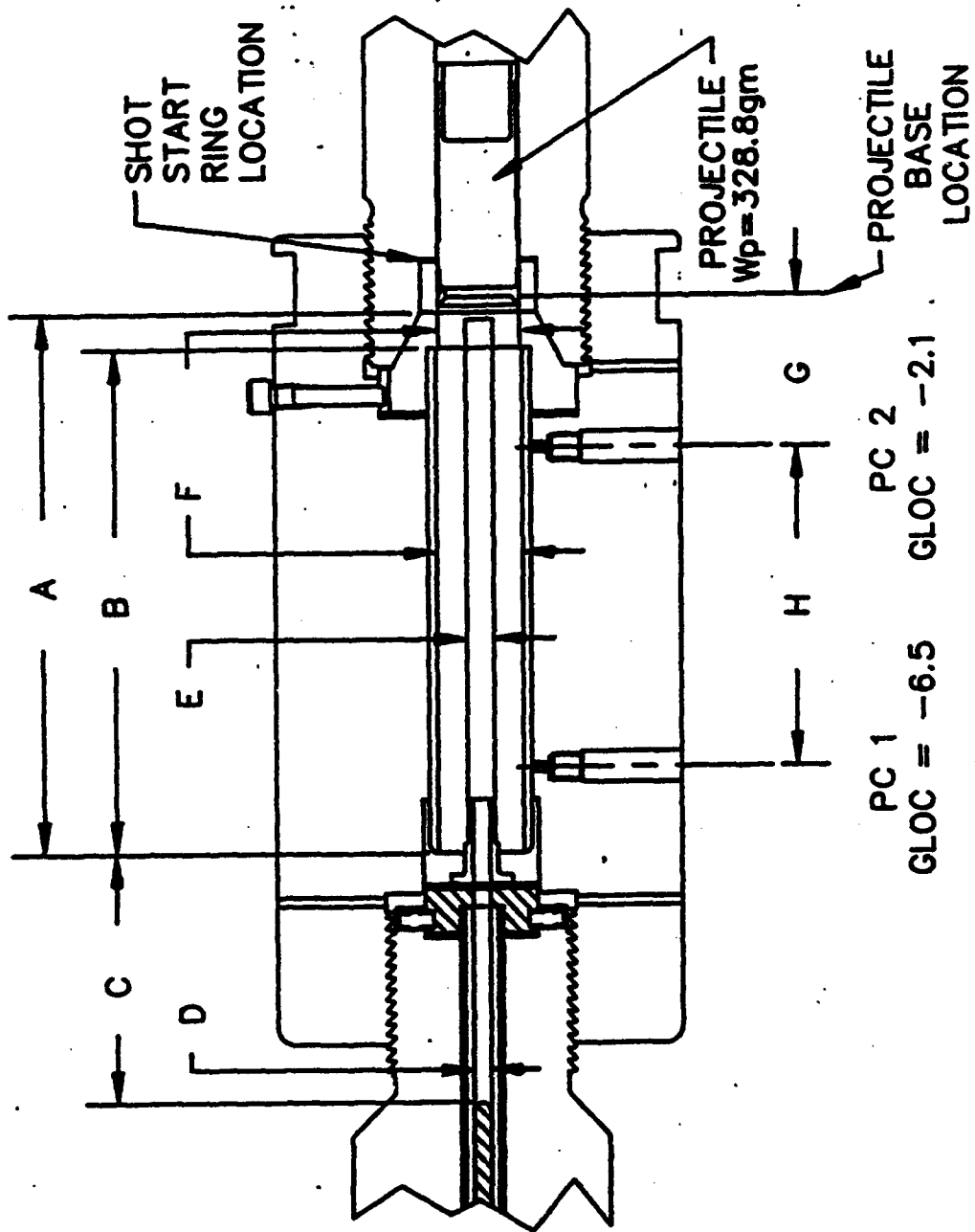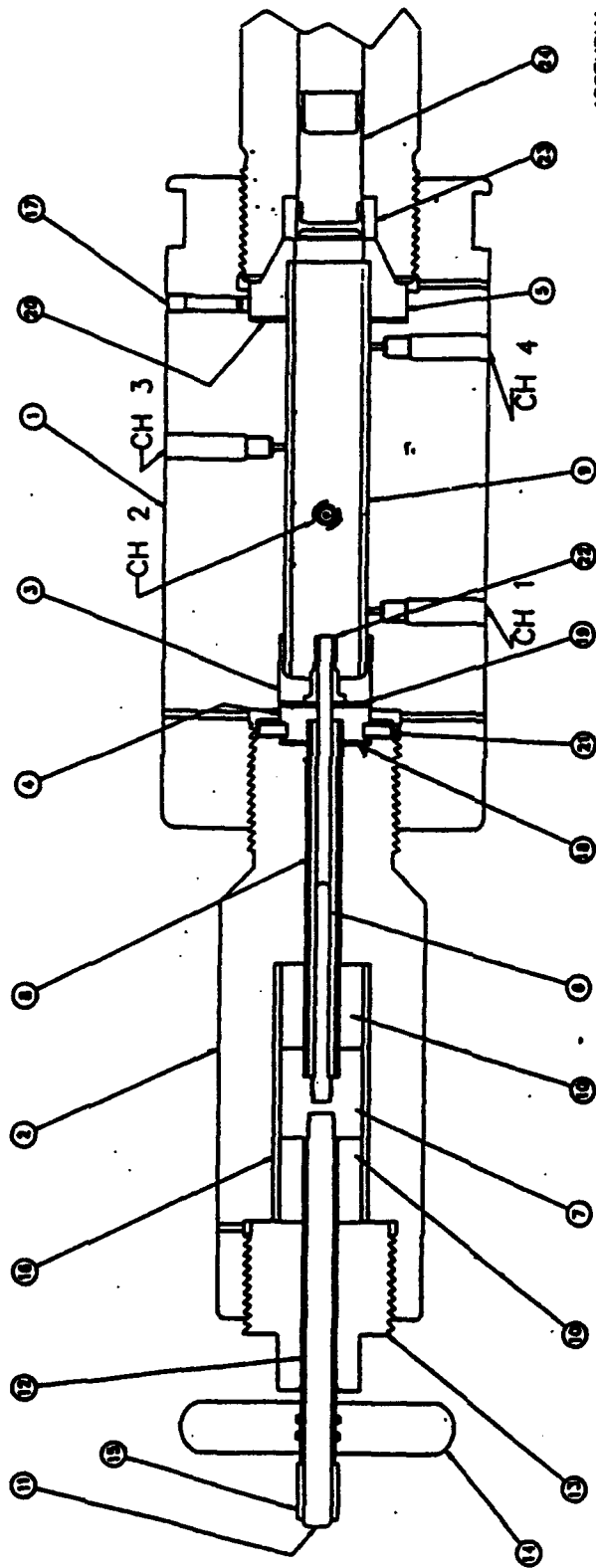
ASSEMBLY
AXIAL CARTRIDGE
210-2-060C

CH 1

CH 2

CH 3

CH 4

ET GUN

LB   RB   PPB

157
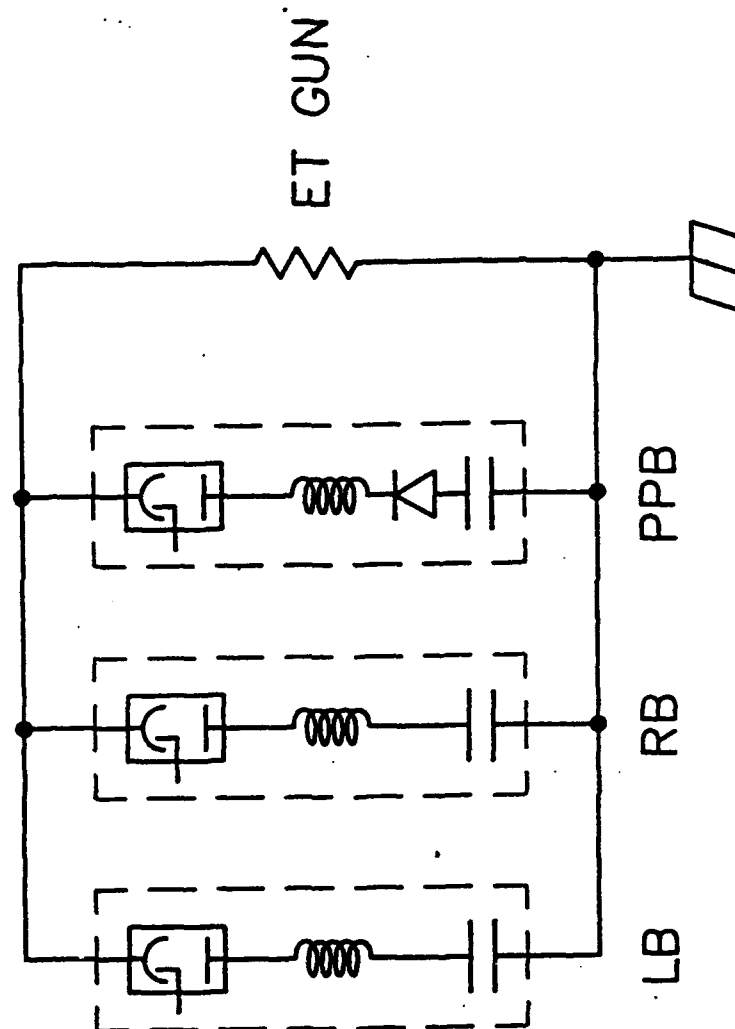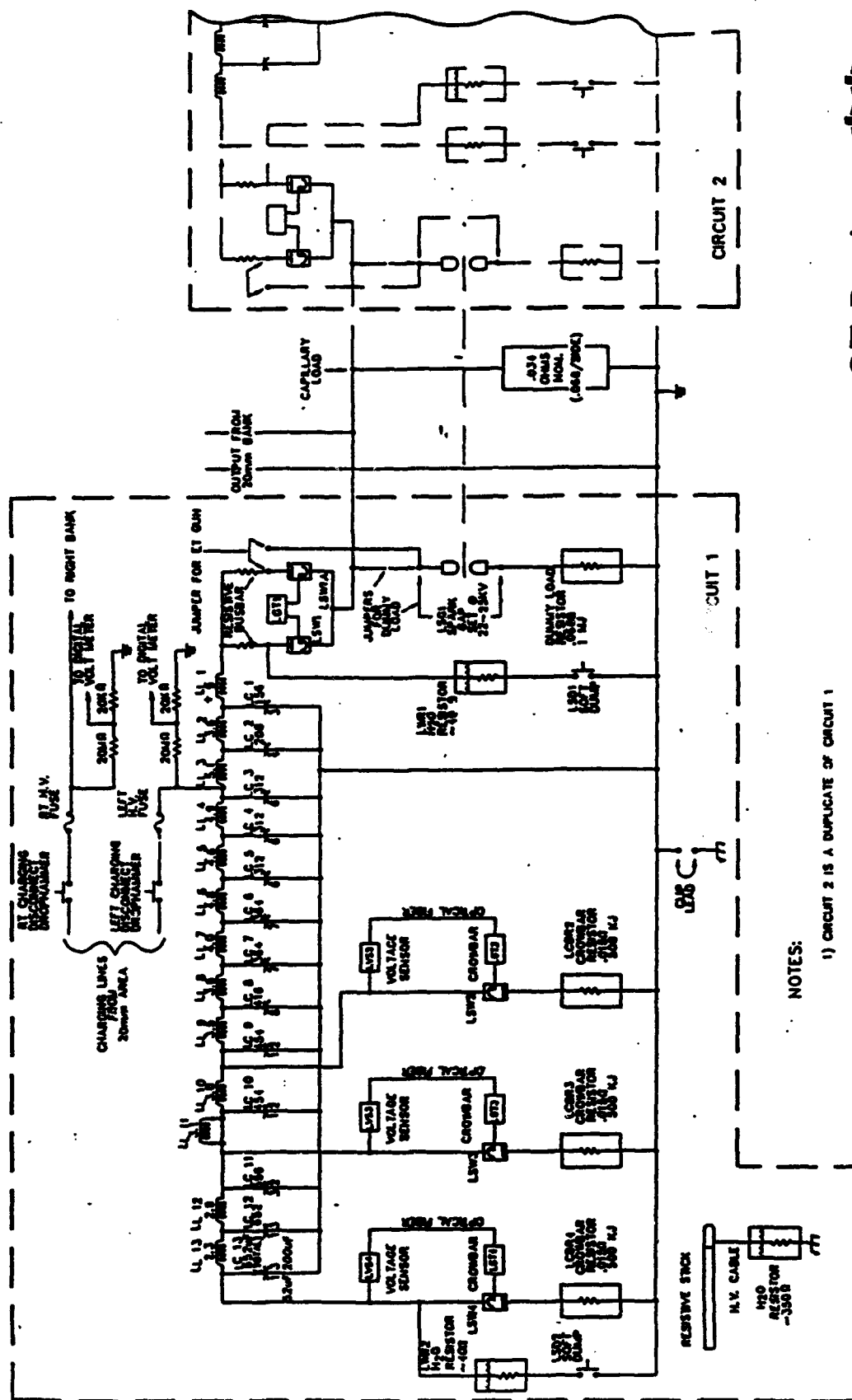
GT-Devices

SCHEMATIC DIAGRAM
30mm PFN

CIRCUIT 2

CIRCUIT 1

NOTES:

1) CIRCUIT 2 IS A DUPLICATE OF CIRCUIT 1

21A-6-193

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Alternate Propellants
OCC Series

OCC02 —— OCC06 —— OCC10

Time (ms)

Power (MW)

159

**Alternate Propellants**
OCC Series

OCC05 ———  OCC06 ———  OCC08

Time (ms)

Power (MW)
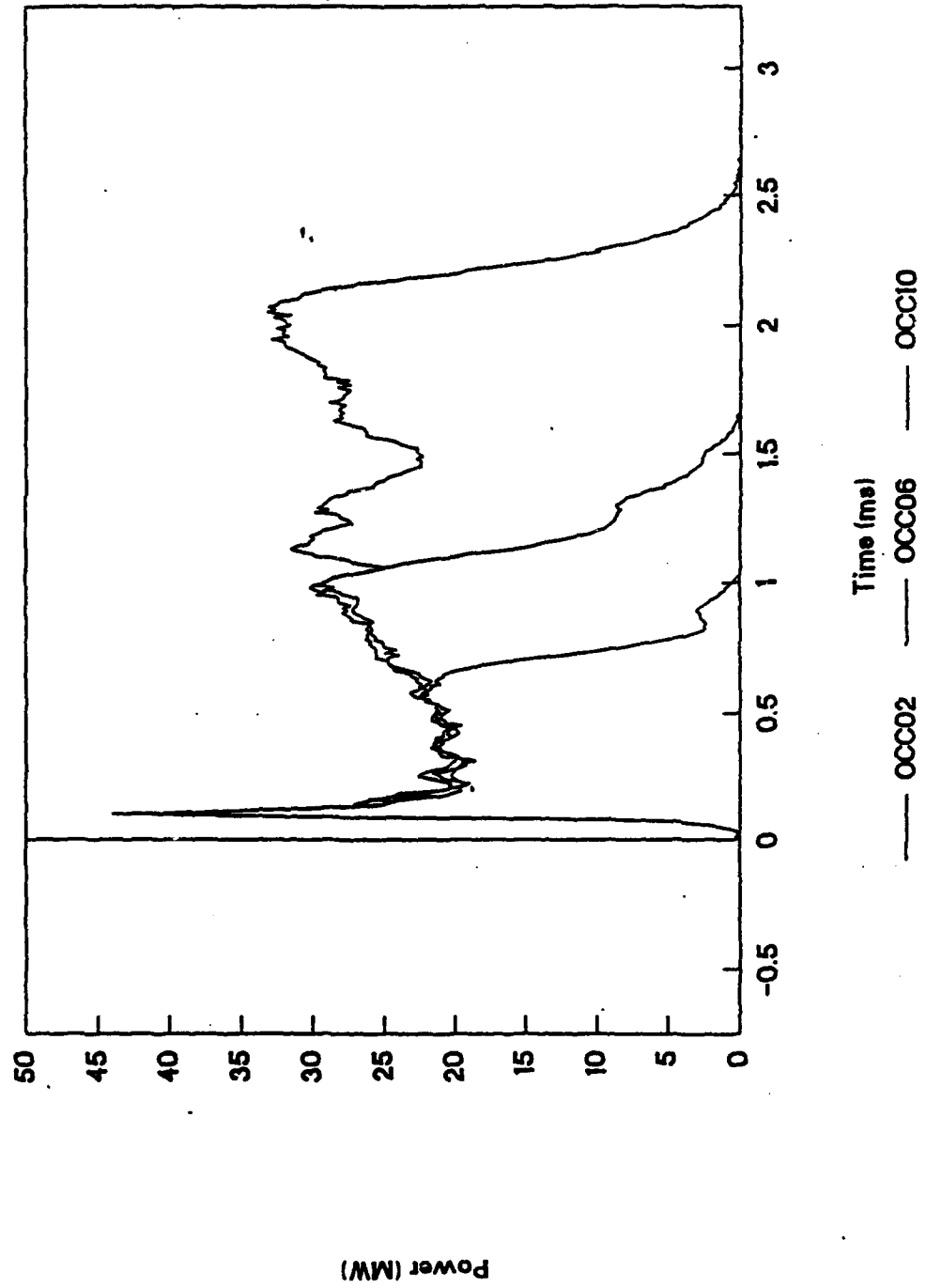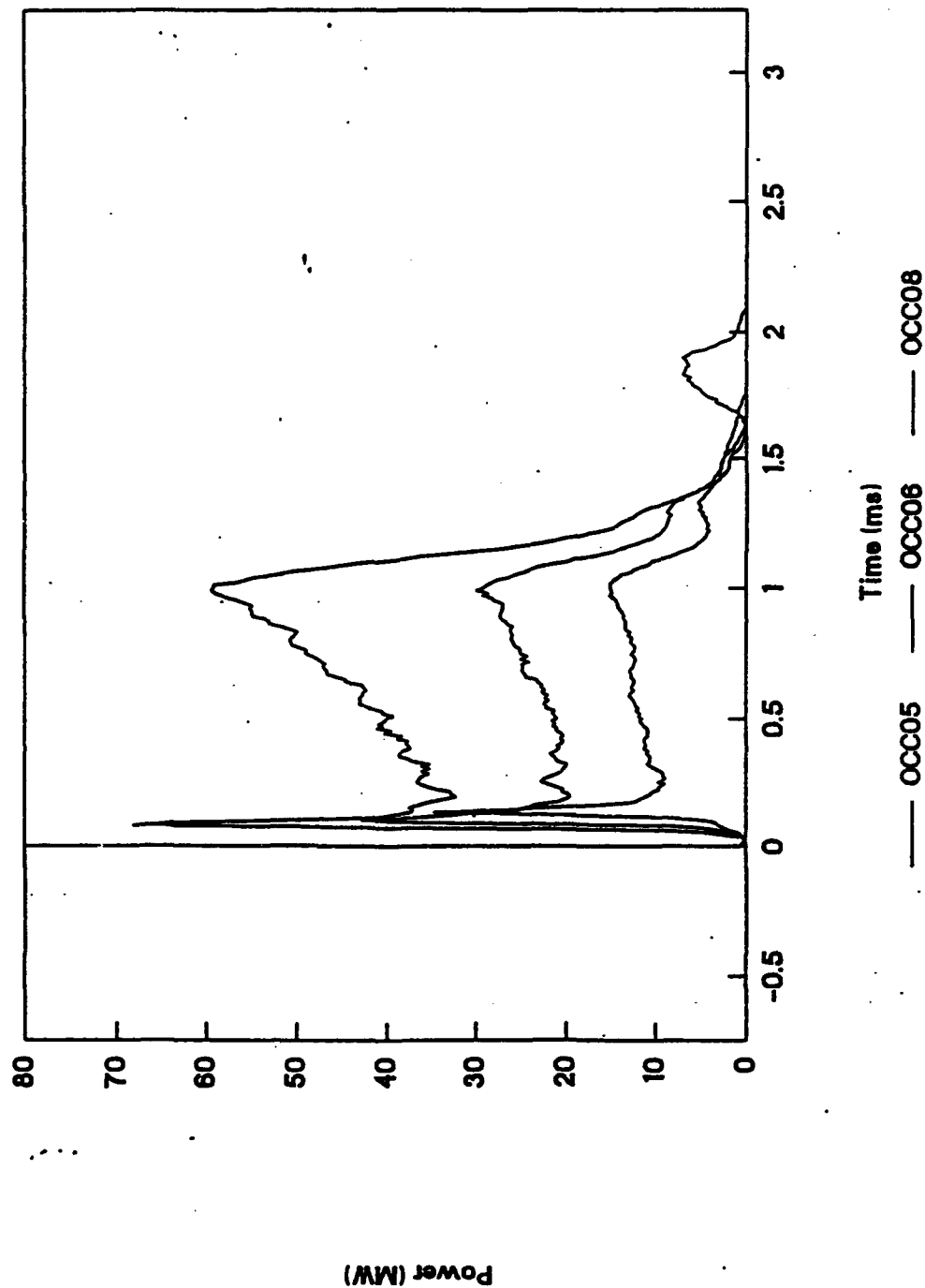
# IBHVG2 PREDICTIONS FOR CENTER CORE BURNING JA2 MONOLITHS

| CHARGE | P(KSI) | V(M/S) | %BURNT |
|--------|--------|--------|--------|
| 1/4    | 2      | 146    | 0.4    |
| 1/2    | 6      | 221    | 0.6    |
| 1      | 13     | 334    | 0.7    |

# JA-2  PRESHOT IBHVG2 RESULTS
## 2.4 MSEC AT 0.5 MJ/KG EE



TIME (MSEC)

PRESSURE (PSI)

162
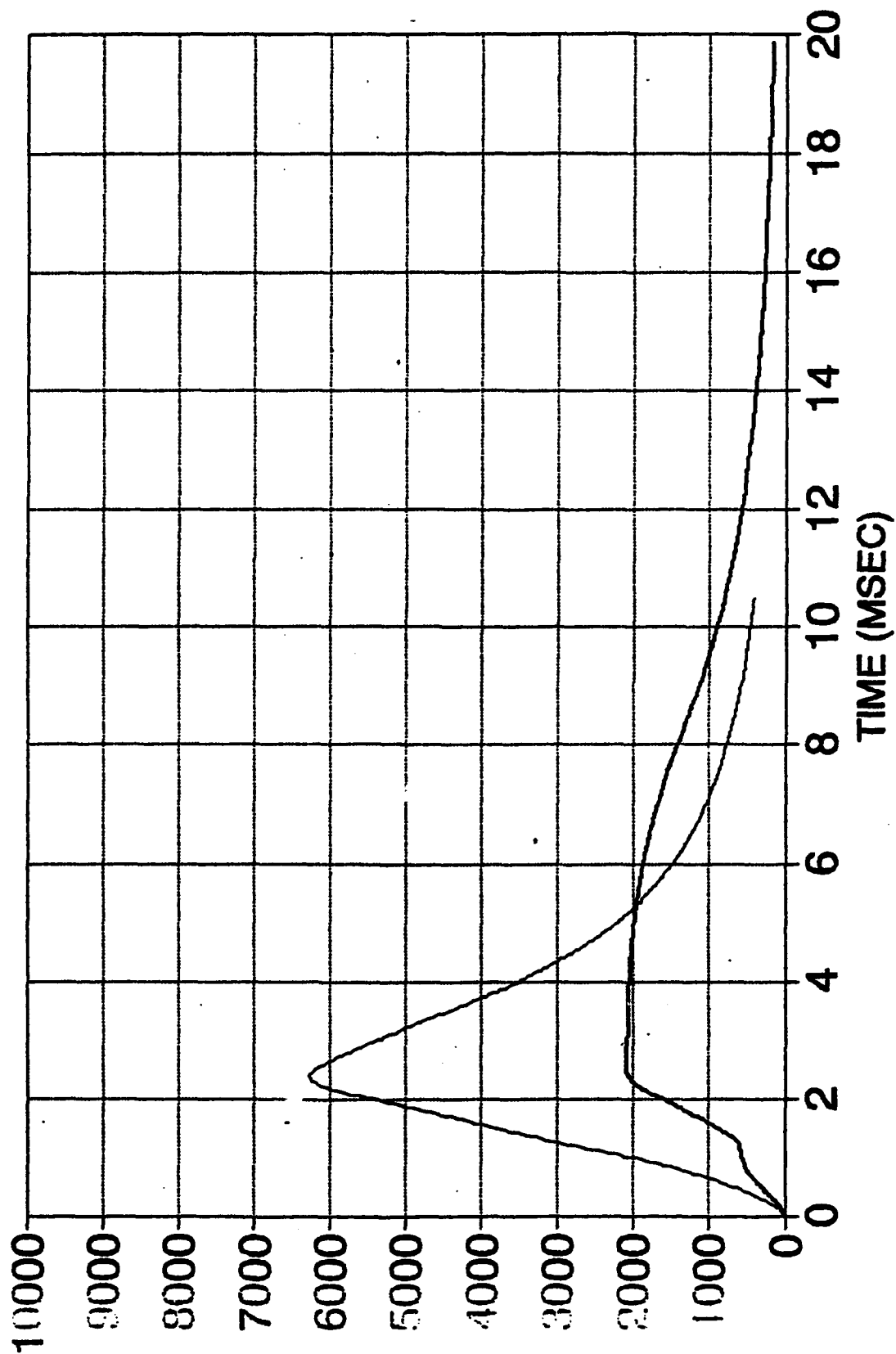
—— QUARTER CHG ——— HALF CHARGE

## Firing Schedule
## As Fired

May 3 , 1993

| Shot Number /Date | Charge Weight | Power Pulse Length (ms) | Energy Density (kJ/gm) | (kV) | | |
|---|---|---|---|---|---|---|
| 1  4/08/93 | 1/4 | 2.2 | .75 | 2.6 | -LB+RB | |
| 2  4/08/93 | 1/2 | 2.2 | .75 | 3.7 | -LB+RB | |
| 3. 4/14/93 | 3/4 | 2.2 | .75 | 4.6 | -LB+RB | |
| 4  4/14/93 | F | 2.2 | .75 | 5.3 | -LB+RB | |
| 5  4/15/93 | 1/4 | 1.1 | .37 | 2.6 | -LB | |
| 6  4/15/93 | 1/2 | 1.1 | .37 | 3.7 | -LB | |
| 7  4/16/93 | 1/4 | 1.1 | 0.75 | 3.7 | -LB | |
| 8  4/16/93 | 1/2 | 1.1 | 0.75 | 5.2 | -LB | |
| 9  4/20/93 | 1/4 | 0.6 | .2 | 2.6 | -½LB | |
| 10 4/20/93 | 1/2 | 0.6 | .2 | 3.7 | -½LB | |
| 11 4/21/93 | 1/4 | 1.1 | 0.75 | 3.7 | -½LB | Mod Tube |
| 12 4/21/93 | 1/2 | 1.1 | 0.75 | 5.2 | -½LB | Mod Tube |
| 13 4/22/93 | 1/2 | 2.2 | 0.75 | 3.7 | -½LB | Mod Tube |
| 14 4/22/93 | 1/4 | 0.6 | 0.75 | 5.2 | -½LB | Mod Tube |
| 15 4/27/93 | 3/4 | 2.2 | 0.75 | 4.6 | -LB+RB | Mod Tube |
| 16 4/27/93 | F | 2.2 | 0.75 | 5.3 | -LB+RB | Mod Tube |
| 17 4/28/93 | 3/4 | 2.2 | 0.37 | 3.25 | -LB+RB | Mod Tube |
| 18 4/28/93 | F | 2.2 | 0.37 | 3.7 | -LB+RB | Mod Tube |

LB - 30mm Left Bank
RB - 30mm Roght Bank

LB+RB - LB fired first, RB fired after delay of 1050µs.
LB    - LB alone.
½LB   - LB with LL9 disconnected from LC8.

30MM AXIAL CARTRIDGE DATA BASE
REVISED 4/93 FOR OLIN 'C' SERIES DATA

| SHOT NUMB | DATE | PROJ MASS GM | PROP FILL GM | CART ENER KJ | PROJ VEL KM/SEC | COMPRESS VEL KM/SEC | PEAK VOLTS KV | CHBR POWER MEG W | CHBR PRESS KPSI | EXTENDED NOTES AND COMMENTS | CHAMBER VOLUME (CK3) | ENERGY DENSITY KJ/GM | SHOT NUMB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 04/08/93 | 332.3 | 61.3 | 30 | 0.319 | | 2.60 | 16 | 10 | JA-3 7. NGLE PERF SINGLE GRAIN 1/4 CHARGE; 0.75KJ/GM 2.2ms PULSE | 161.0 | 0.74 | 1 |
| 2 | 04/08/93 | 332.3 | 83.8 | 58 | 0.478 | | 3.68 | 33 | 18 | JA-2 (SPSG) 1/2 CHARGE 2.2ms PULSE | 161.9 | 0.70 | 2 |
| 3 | 04/14/93 | 332.6 | 130.8 | 77 | 0.480 | | 4.60 | 47 | 27 | JA-2 (SPSG) 3/4 CHARGE; 2.2ms PULSE; MODS. TO HOLD GRAIN | 161.0 | 0.59 | 3 |
| 4 | 04/14/93 | 331.9 | 176.1 | 111 | 0.547 | | 5.30 | 68 | 30 | JA-2 (SPSG) FULL CHARGE; 0.75KJ/GM 2.2ms PULSE | 161.0 | 0.63 | 4 |
| 5 | 04/15/93 | 333.1 | 41.3 | 15 | 0.271 | | 2.60 | 15 | 10 | JA-2 (SPSG) 1/4 CHARGE; 0.37KJ/GM 1.1ms PULSE (LEFT BANK) | 161.0 | 0.37 | 5 |
| 6 | 04/15/93 | 332.1 | 85.1 | 28 | 0.386 | | 3.70 | 30 | 17 | JA-2 (SPSG) 1/2 CHARGE; 0.37KJ/GM 1.1ms PULSE; SM PROP LEFT IN CHBR | 16140 | 0.33 | 6 |
| 7 | 04/16/93 | 329.1 | 41.2 | 29 | 0.342 | | 3.70 | 30 | 11 | JA-2 (SPSG) 1/4 CHARGE; 0.75KJ/GM 1.1ms PULSE (OCCO1 W/SHORT PULSE) | 161.0 | 0.70 | 7 |
| 8 | 04/16/93 | 328.6 | 84.9 | 54 | 0.433 | | 5.20 | 60 | 19 | JA-2 (SPSG) 1/2 CHARGE; 0.75KJ/GM 1.1ms PULSE (OCCO2 W/SHORT PULSE) | 161.0 | 0.63 | 8 |
| 9 | 04/20/93 | 329.2 | 41.0 | 8 | 0.192 | | 2.60 | 12 | 7 | JA-2 (SPSG) 1/4 CHARGE; 0.2KJ/GM 0.6ms PULSE; PAINTED PROPELLANT | 161.0 | 0.20 | 9 |
| 10 | 04/20/93 | 329.5 | 84.7 | 15 | -.260 | | 3.70 | 22 | 17 | JA-2 (SPSG) 1/2 CHARGE; 0.2KJ/GM 0.6ms PULSE; BAD VELOCITY DATA | 161.0 | 0.18 | 10 |
| 11 | 04/21/93 | 329.1 | 38.5 | 30 | 0.162 | | 3.70 | 32 | 5 | JA-2 (SPSG) 1/4 CHARGE; 0.75KJ/GM 1.1ms PULSE W/MOD TUBE; NO VEL 3 | 161.0 | 0.78 | 11 |
| 12 | 04/21/93 | 328.8 | 78.9 | 54 | 0.358 | | 5.20 | 55 | 20 | JA-2 (SPSG) 1/2 CHARGE; 0.75KJ/GM 1.1ms PULSE W/MOD TUBE | 161.0 | 0.69 | 12 |
| 13 | 04/22/93 | 329.0 | 78.0 | 57 | 0.365 | | 3.70 | 31 | 18 | JA-2 (SPSG) 1/2 CHARGE; 0.75KJ/GM 2.2ms PULSE; MOD TUBE;PROP INTACT | 161.0 | 0.73 | 13 |
| 14 | 04/22/93 | 329.5 | 38.5 | 30 | 0.218 | | 5.20 | 47 | 6 | JA-2 (SPSG) 1/4 CHARGE; 0.6ms PULSE MOD TUBE;PROJ TUMBLED | 161.0 | 0.77 | 14 |
| 15 | 04/27/93 | 328.3 | 120.5 | 86 | 0.426 | | 4.60 | 48 | 13 | JA-2 (SPSG) 3/4 CHARGE; 0.75KJ/GM 2.2ms PULSE MOD TUBE;GRAIN RECOV. | 161.0 | 0.71 | 15 |
| 16 | 04/27/93 | 328.9 | 162.5 | 102 | 0.554 | | 5.30 | 64 | 31 | JA-2 (SPSG) FULL CHARGE; 0.75KJ/GM 2.2ms PULSE; W/ MODERATOR TUBE | 161.0 | 0.63 | 16 |
| 17 | 04/28/93 | 329.0 | 121.4 | 46 | 0.322 | | 3.25 | 26 | 11 | JA-2 (SPSG) 3/4 CHARGE; 0.37KJ/GM 2.2ms PULSE W/ MODERATOR TUBE | 161.0 | 0.38 | 17 |
| 18 | 04/28/93 | 328.9 | 156.2 | 59 | -.330 | | 3.70 | 32 | 16 | JA-2 (SPSG) FULL CHARGE; 0.37KJ/GM 2.2ms PULSE MOD TUBE; BAD VELOC. | 161.0 | 0.37 | 18 |

Polycarbonate
0.125"

Shot OCCΦ1 and Φ2.

166

Steel washer

Polycarbonate
0.25"

0.625"

Shots occ φ3 — φ8

167

Steel washer

G10 0.71"

0.615"

Shot OCC∅9 – 14

168

New Barrel Seal.

G10 0.71"

0.625"

Shots Occ 15 - 18

169
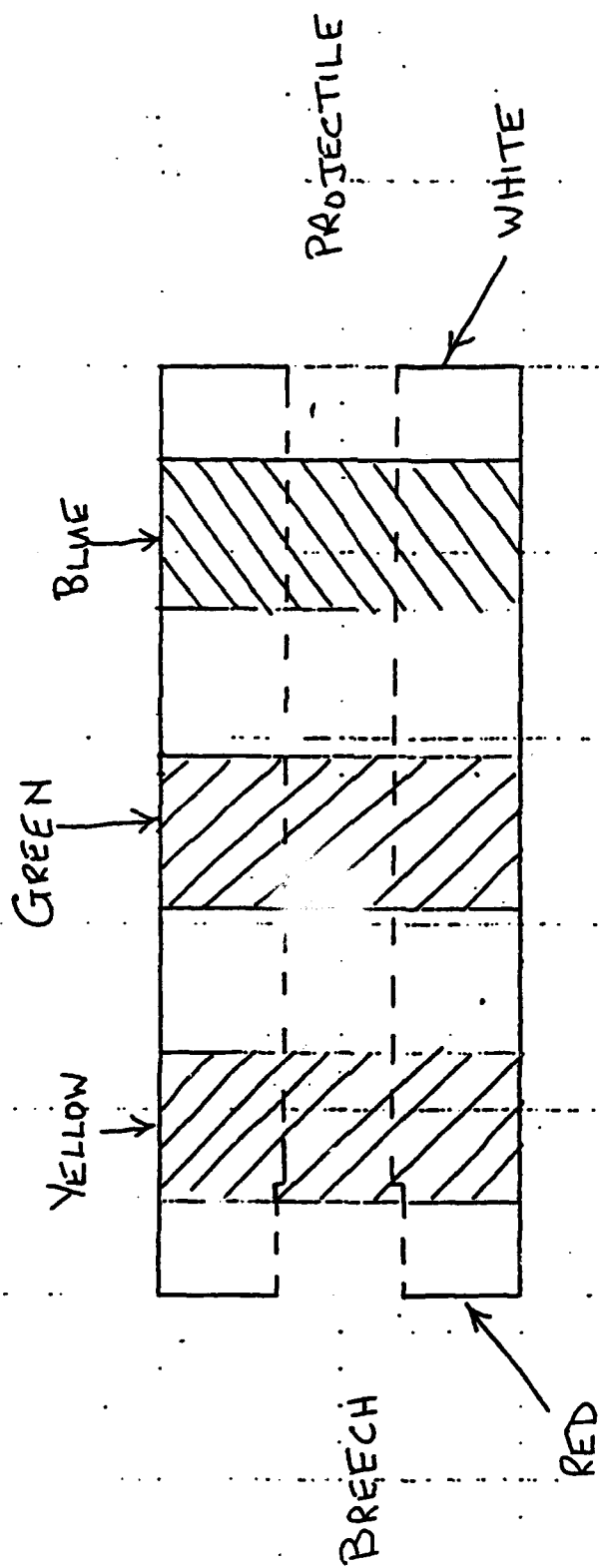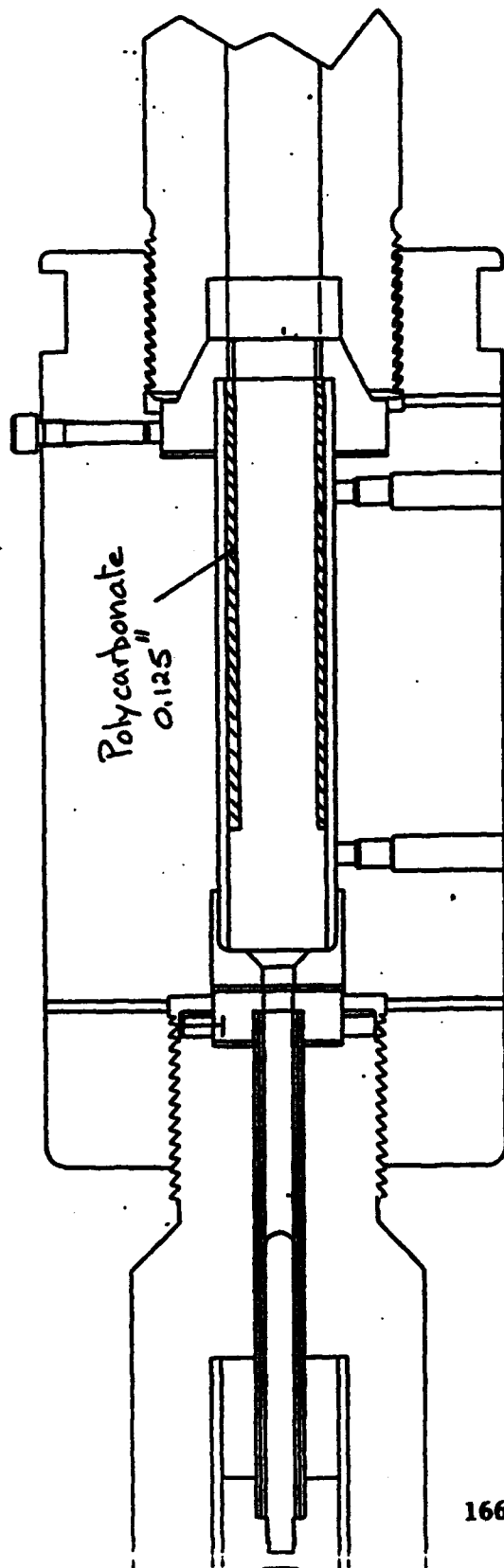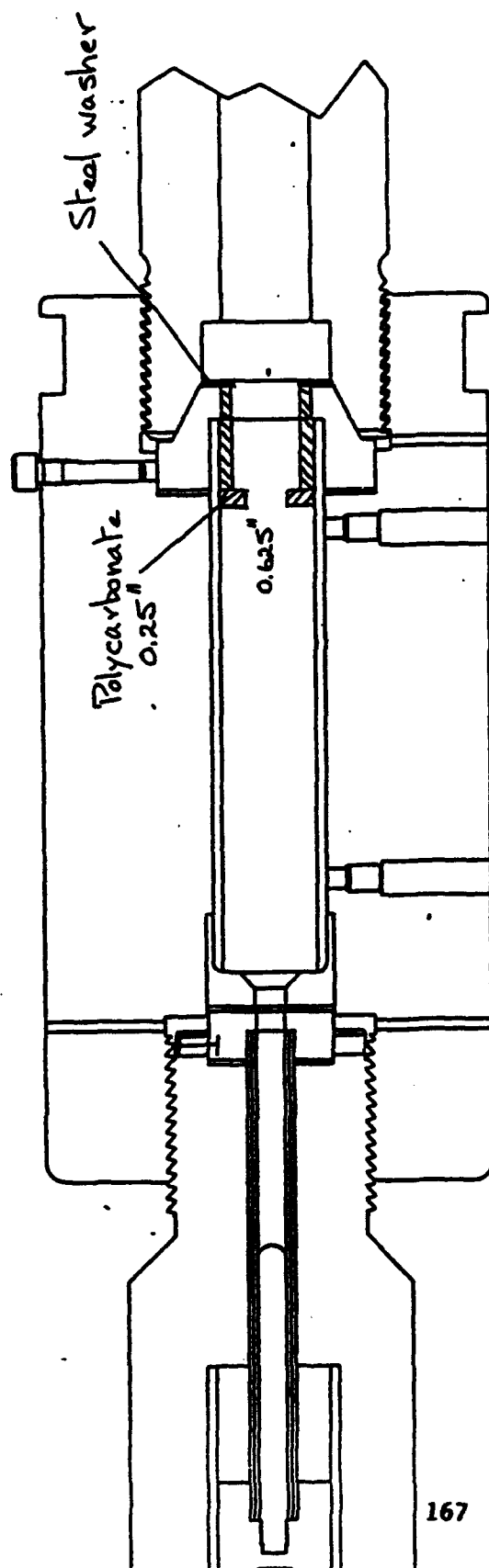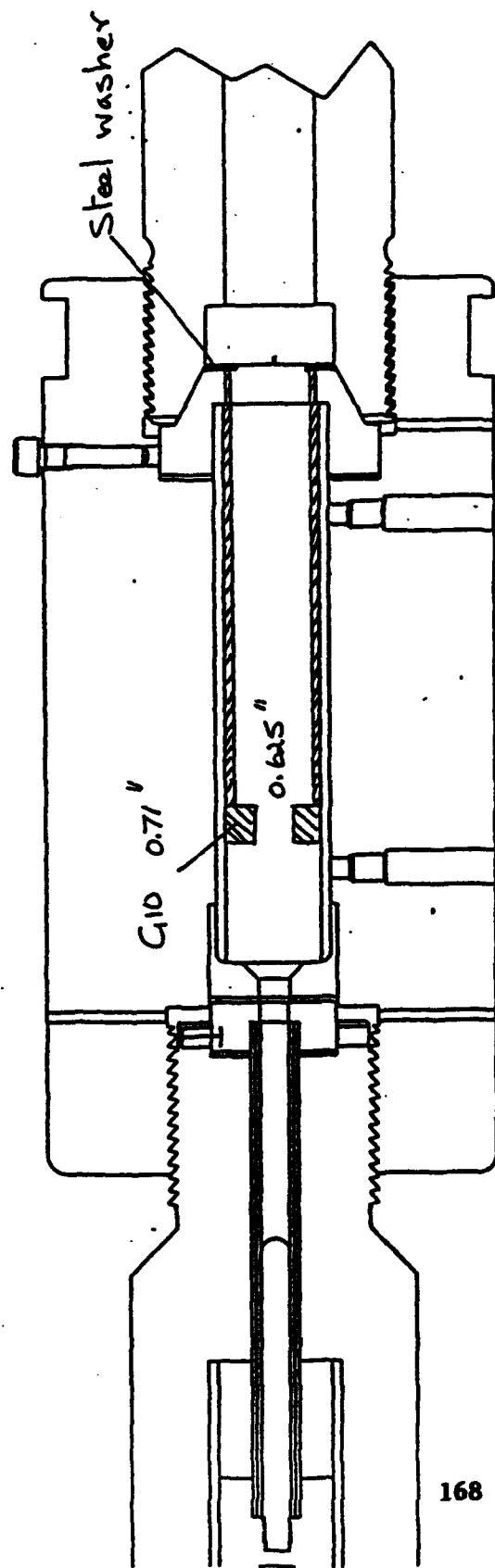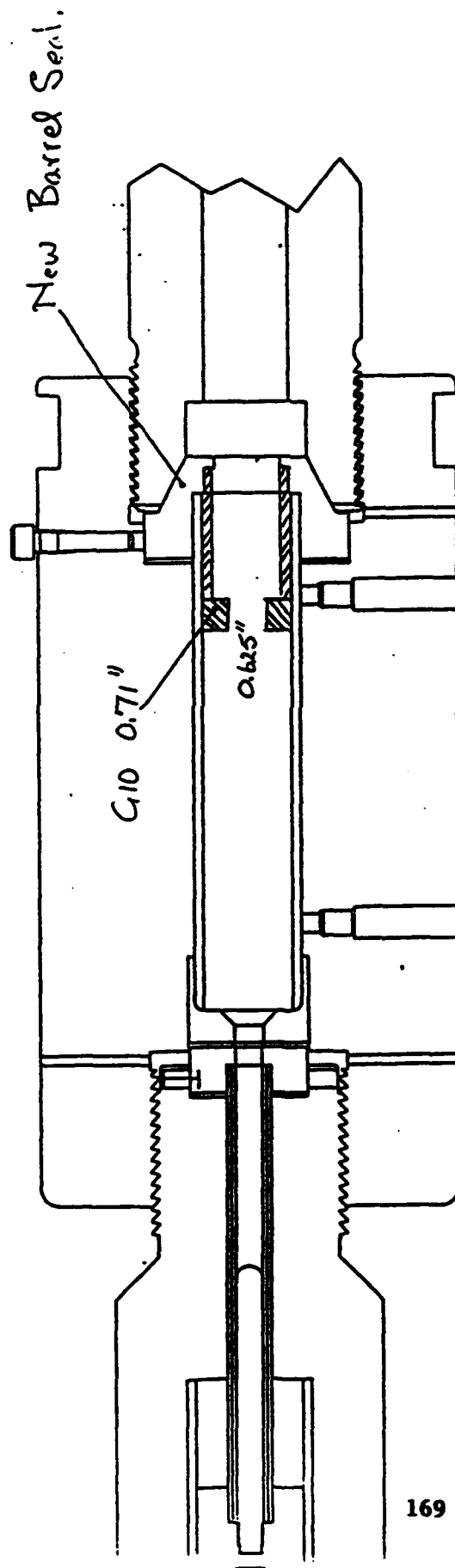
| SHOT NUMB | Notes on retainer system | Retainer System |
|---|---|---|
| 1 | Insert tube pushed slightly into barrel. | I |
| 2 | Insert tube stuck in barrel, > 1 inch. | I |
| 3 | All retainers launched. | II |
| 4 | All retainers launched. | II |
| 5 | Nozzle melted, tube in place, melted. | II |
| 6 | Ring launched, tube in chamber. | II |
| 7 | Ring launched, tube moved forward. | II |
| 8 | Ring launched, tube pushed into barrel. | II |
| 9 | Nozzle melted, tube in place, ring launched. | III |
| 10 | G10 retainer pushed into barrel seal. | III |
| 11 | Inserts in place. | III |
| 12 | Melt down. Liquid in barrel. | III |
| 13 | G10 ring in chamber, tube pushed into barrel seal. | III |
| 14 | All retainers in place. | III |
| 15 | All retainers in place. | IV |
| 16 | Retainers launched. | IV |
| 17 | G10 ring pushed into barrel seal, tube launched. | IV |
| 18 | Steel ring in place. | IV |

170

# JA2 MONOLITHS QUARTER CHARGE

| SHOT | P(MW) | EE(KJ) | V(M/S) | PE(KJ) |
|---|---|---|---|---|
| 1 | 16 | 30 | 316 | 17 |
| 5 | 15 | 15 | 271 | 12 |
| 7 | 30 | 29 | 342 | 19 |
| 9 | 12 | 8 | 192 | 6.1 |
| 11 MT | 32 | 30 | 162· | 4.4 |
| 14 MT | 47 | 30 | 218 | 7.9 |
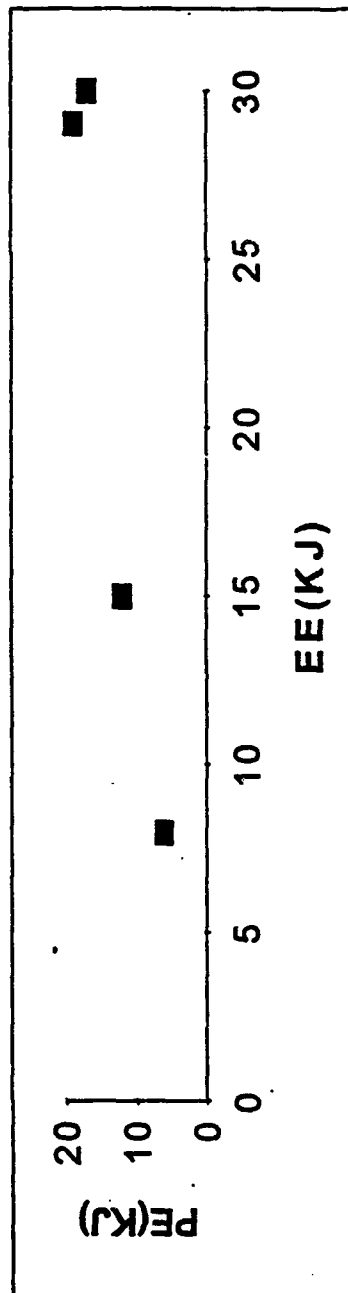
# JA2 MONOLITHS
# HALF CHARGE

| SHOT | P(MW) | EE(KJ) | V(M/S) | PE(KJ) |
|------|-------|--------|--------|--------|
| 2 | 33 | 58 | 478 | 38 |
| 6 | 30 | 28 | 386 | 25 |
| 8 | 60 | 54 | 433 | 31 |
| 10 | 22 | 15 | 260 | 11 |
| 12 | 55 | 54 | 358 | 21 |
| 15 | 31 | 57 | 365 | 22 |



PE(KJ) versus EE(KJ)
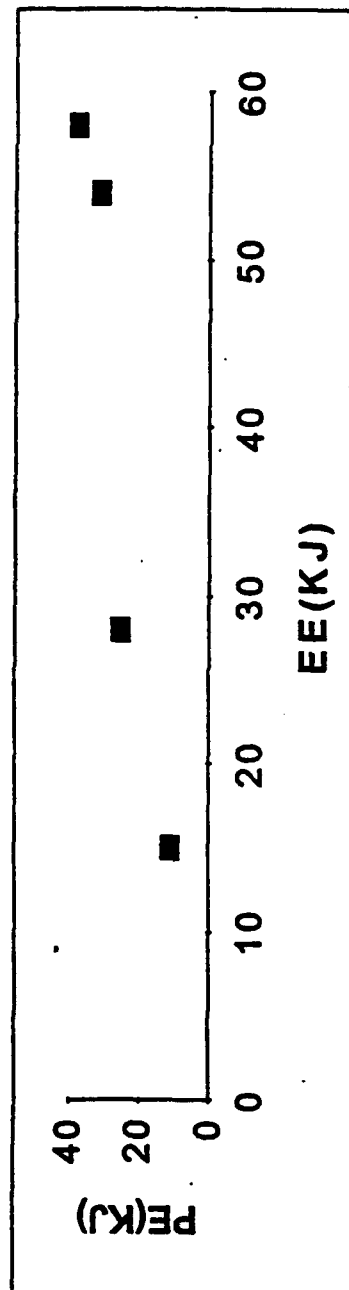
| SHOT NUMB | PROP FILL GM | TANK RESIDUE GM | (tank residue) | Chamber Residue gm | (chamber) | Barrel Residue gm |
|---|---|---|---|---|---|---|
| 1 | 41.3 | 18.4 | Broken not burned | TRACE | | 0.9 |
| 2 | 83.8 | 32.5 | Some burned | 2.2 | one piece, burned | TRACE |
| 3 | 130.8 | 57.8 | 18 chunks, 40 dust | TRACE | | 0.6 |
| 4 | 176.1 | 27.1 | powder | 3.9 | pieces, burned | 0.1 |
| 5 | 41.3 | 10.0 | powder | TRACE | melt down | 0.1 |
| 6 | 85.1 | 48.4 | 28 chunks, 20 powder | 17.3 | cracked, burned | 0.9 |
| 7 | 41.2 | 20.8 | 11 chunks, 10 dust | 18.0 | cracked, burned | 0.1 |
| 8 | 84.9 | 55.0 | 22 chunks, 33 dust | 16.6 | large pieces, burned | TRACE |
| 9 | 41.0 | 21.0 | few chunks, rest dust | TRACE | | 0.4 |
| 10 | 84.7 | 44.7 | 5 chunks, 40 dust | 10.0 | pieces, burned | 0.0 |
| 11 | 38.5 | 7. | dust | 37.8 | whole | 0.1 |
| 12 | 78.9 | 6.3 | dust | TRACE | | LIQUID |
| 13 | 78.0 | 10.9 | dust | 66.8 | cracked, burned | 0.1 |
| 14 | 38.5 | 8.9 | dust | 32.9 | cracked, burned | TRACE |
| 15 | 120.5 | 18.0 | few chunks, rest dust | 109.9 | whole | 0.2 |
| 16 | 162.5 | 69.0 | 26 chunks, 43 dust | 0.2 | | 0.7 |
| 17 | 121.4 | 65.1 | dust | NONE | | NONE |
| 18 | 156.2 | 87.4 | 27 chunks, 61 dust | NONE | | 1.3 |

# Residue

Found in Chamber

1/2 Charge Shot without Moderator Tube

Found in Expansion Tank

+ Dust

OR

Nozzle

Found in Chamber

Burn Surface

3/4 Charge
Shot with Moderator Tube

174
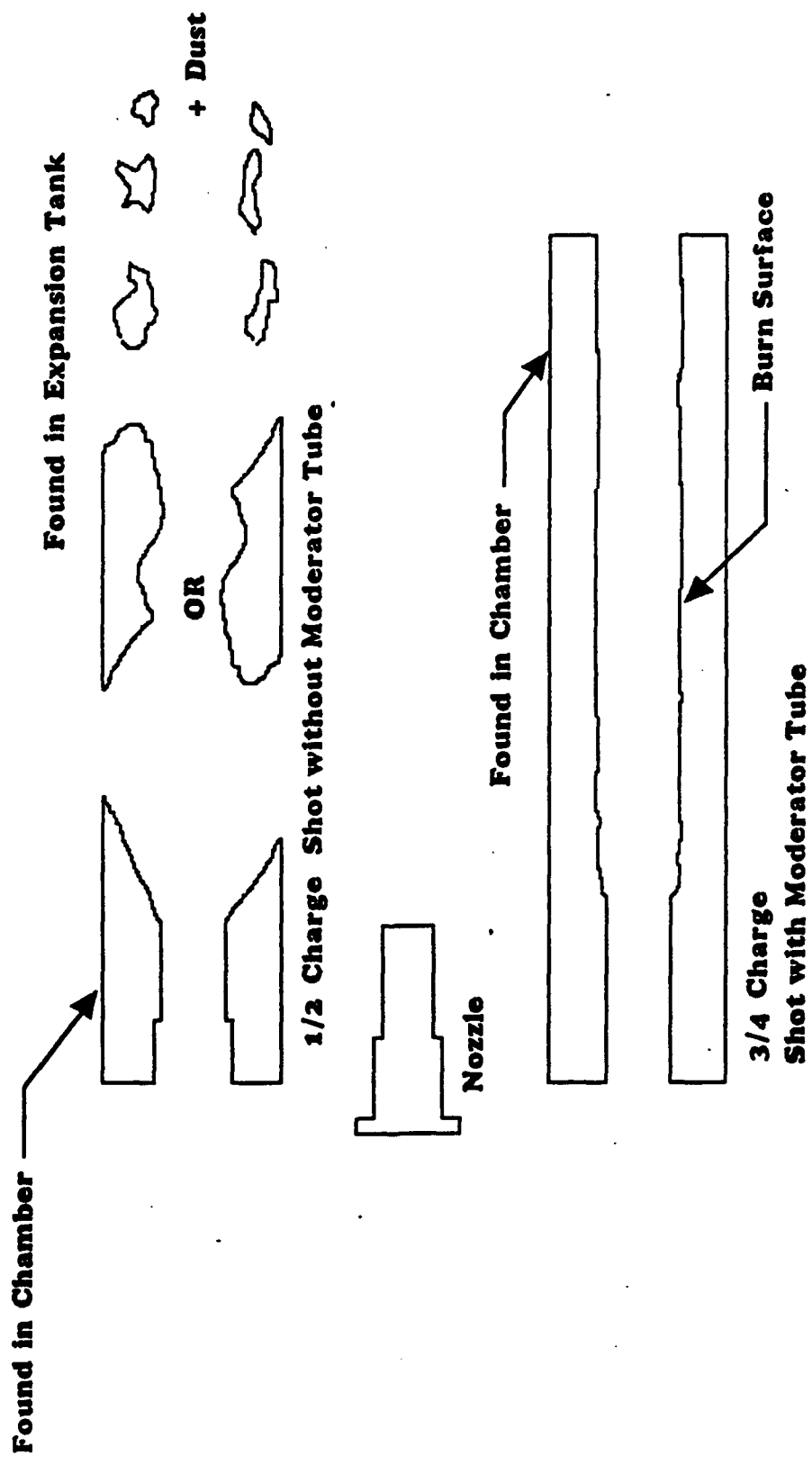
# JA2 MONOLITHS
# BURNING RATES

$r = b \, [Pmean]^{a} + c \, v$

$v = v_P$ proj velocity for prop/gas surface

$v = v_J$ plasma velocity for prop/plasma surface

POWER

OCC01  4-8-93

MEGAWATTS

TIME, ms

34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0

-1.0   -0.0   1.0   2.0   3.0   4.0   5.0   6.0   7.0   8.0   9.0

ALL CHAMBERS

OCC01 4-8-93

——— CHAMBER 1 ——— CHAMBER 2 ——— CHAMBER 3 ——— CHAMBER 4

PRESSURE, Kpsi

TIME, ms

ALL CHAMBERS

OCC02 4-8-93

PRESSURE, Kpsi

TIME, ms

CHAMBER 1 ——— CHAMBER 2 ——— CHAMBER 3 ——— CHAMBER 4
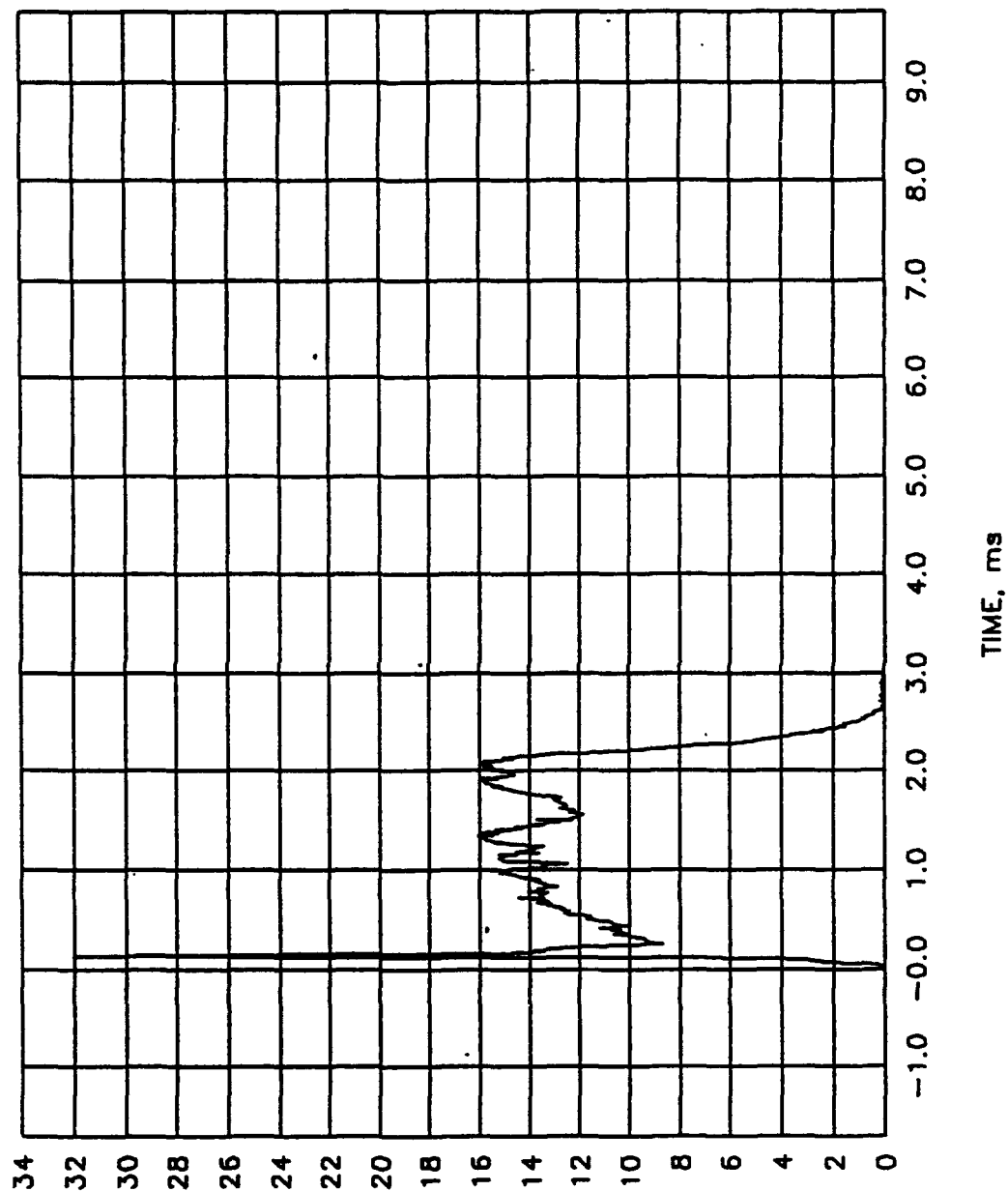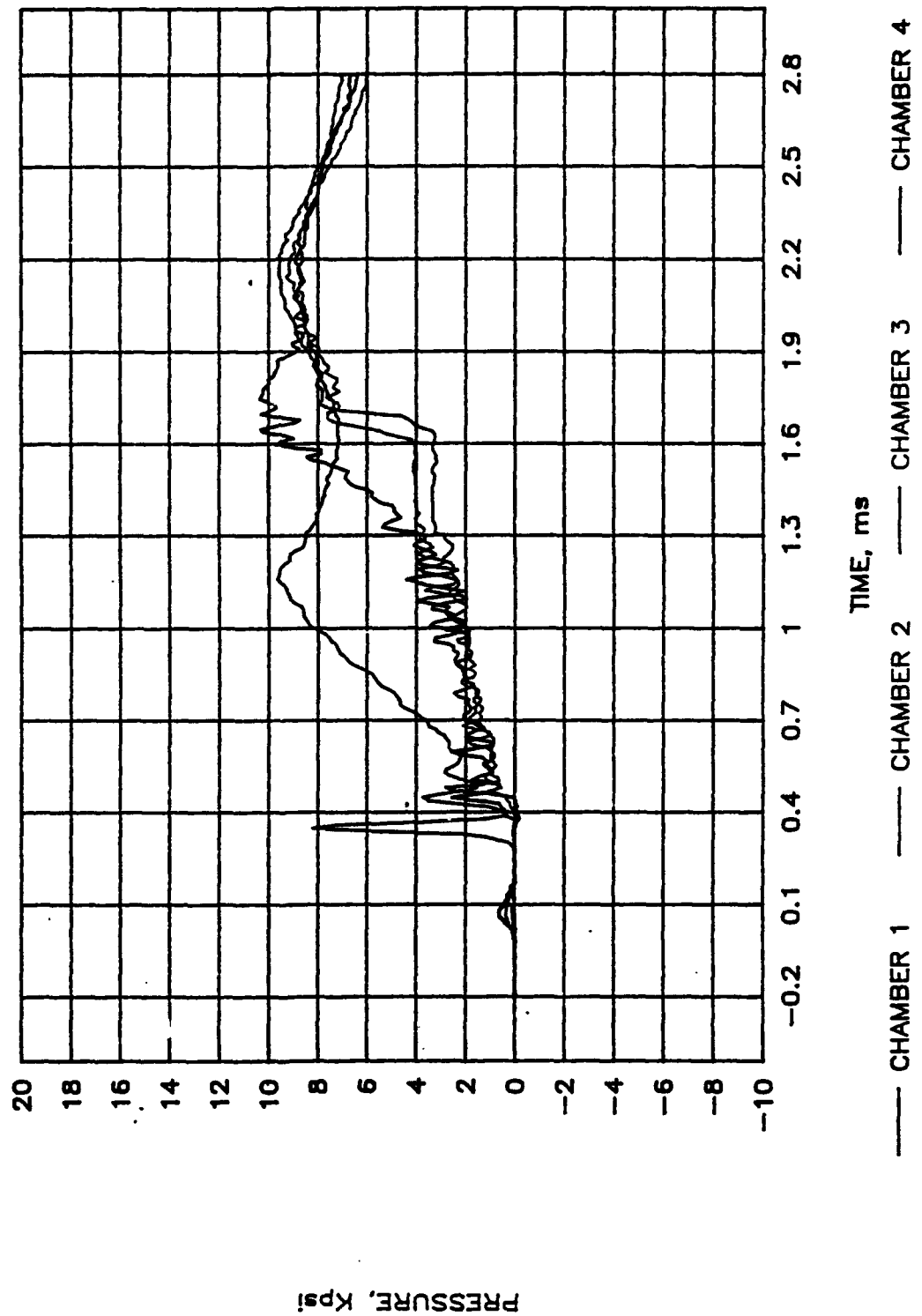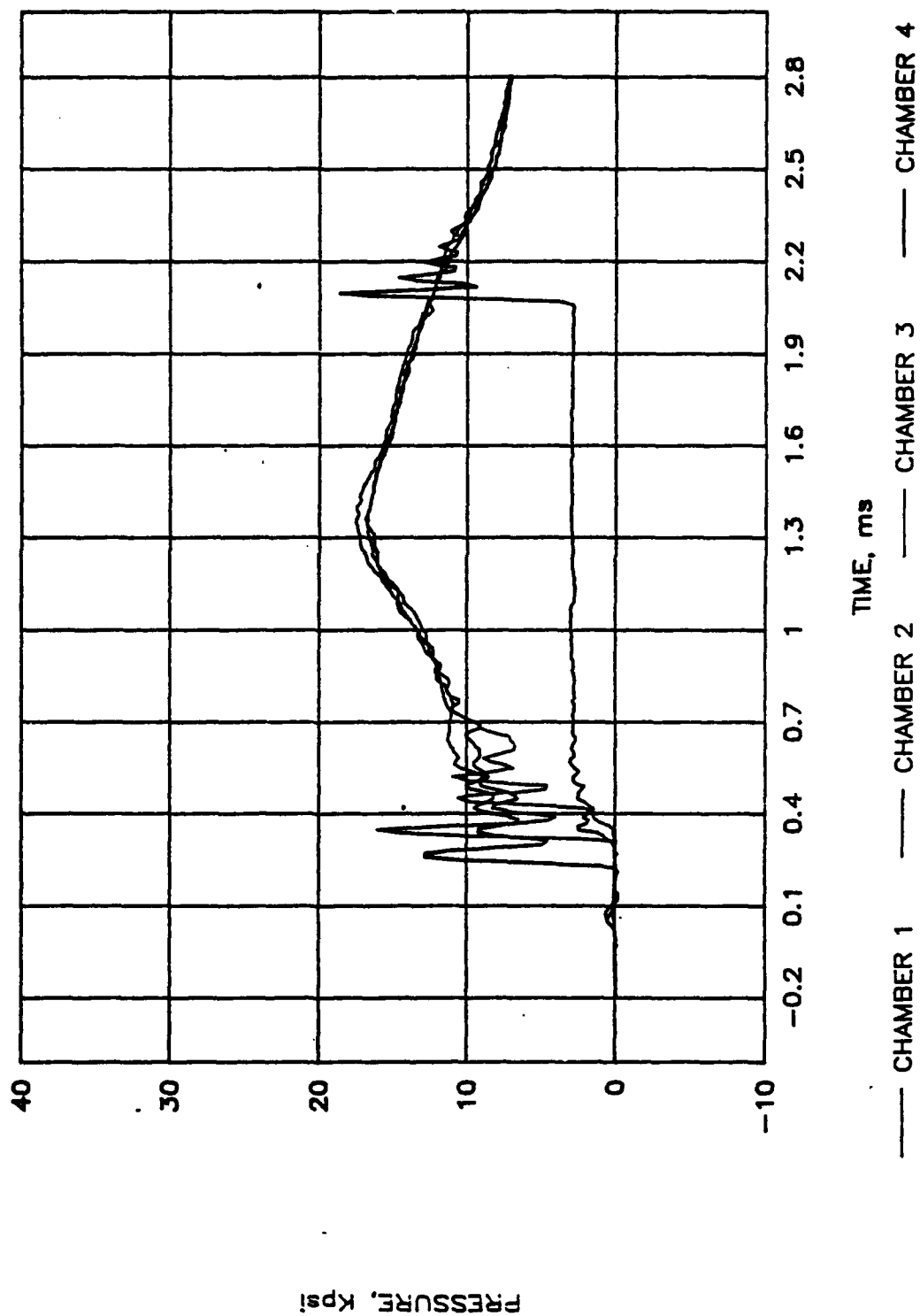
ALL CHAMBERS

OCC03 4-14-93

PRESSURE, Kpsi

TIME, ms

CHAMBER 1 —— CHAMBER 2 —— CHAMBER 3 —— CHAMBER 4

179
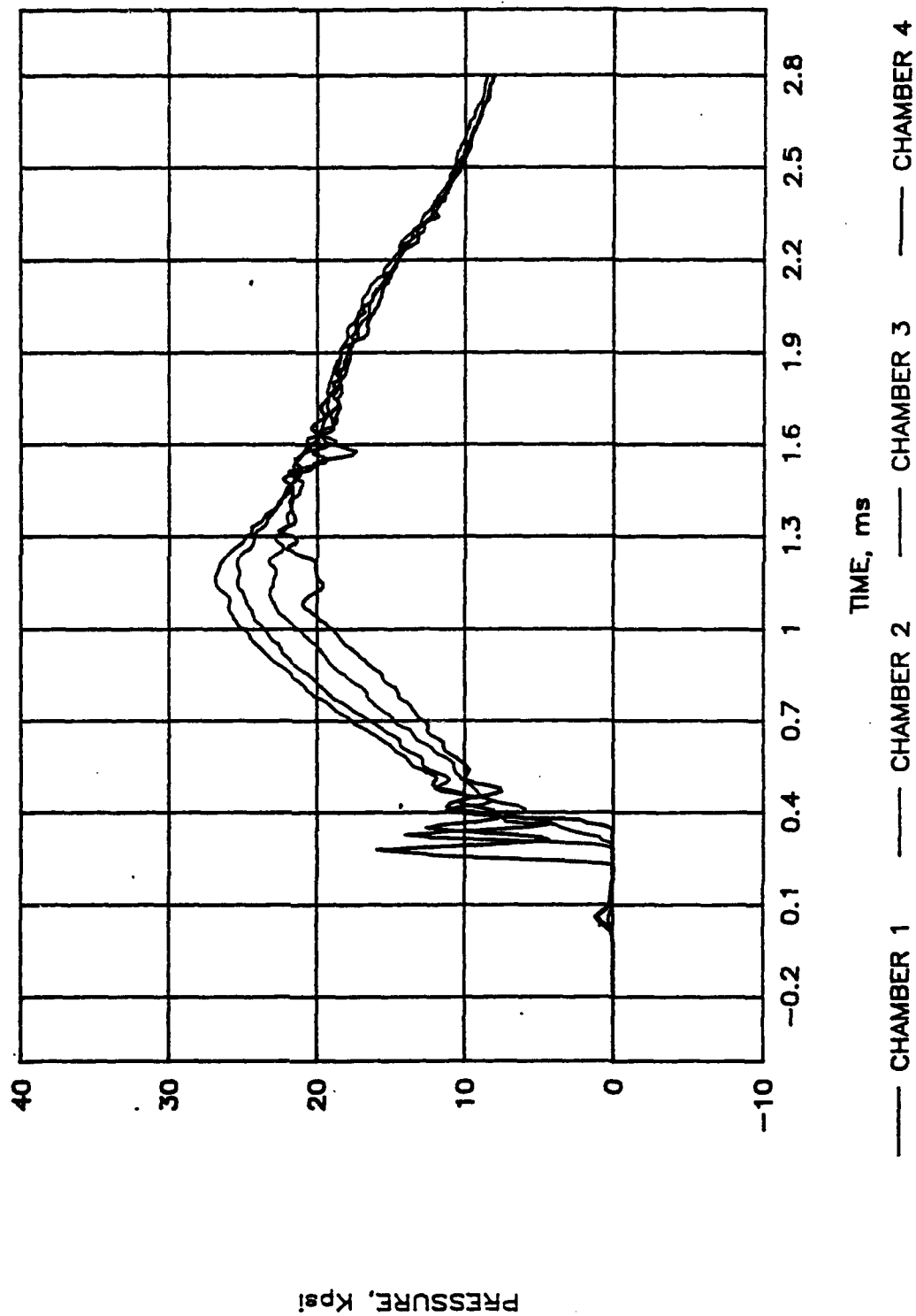
ALL CHAMBERS
OCC04 4-14-93

PRESSURE, kpai

TIME, ms

CHAMBER 1    CHAMBER 2    CHAMBER 3    CHAMBER 4

180
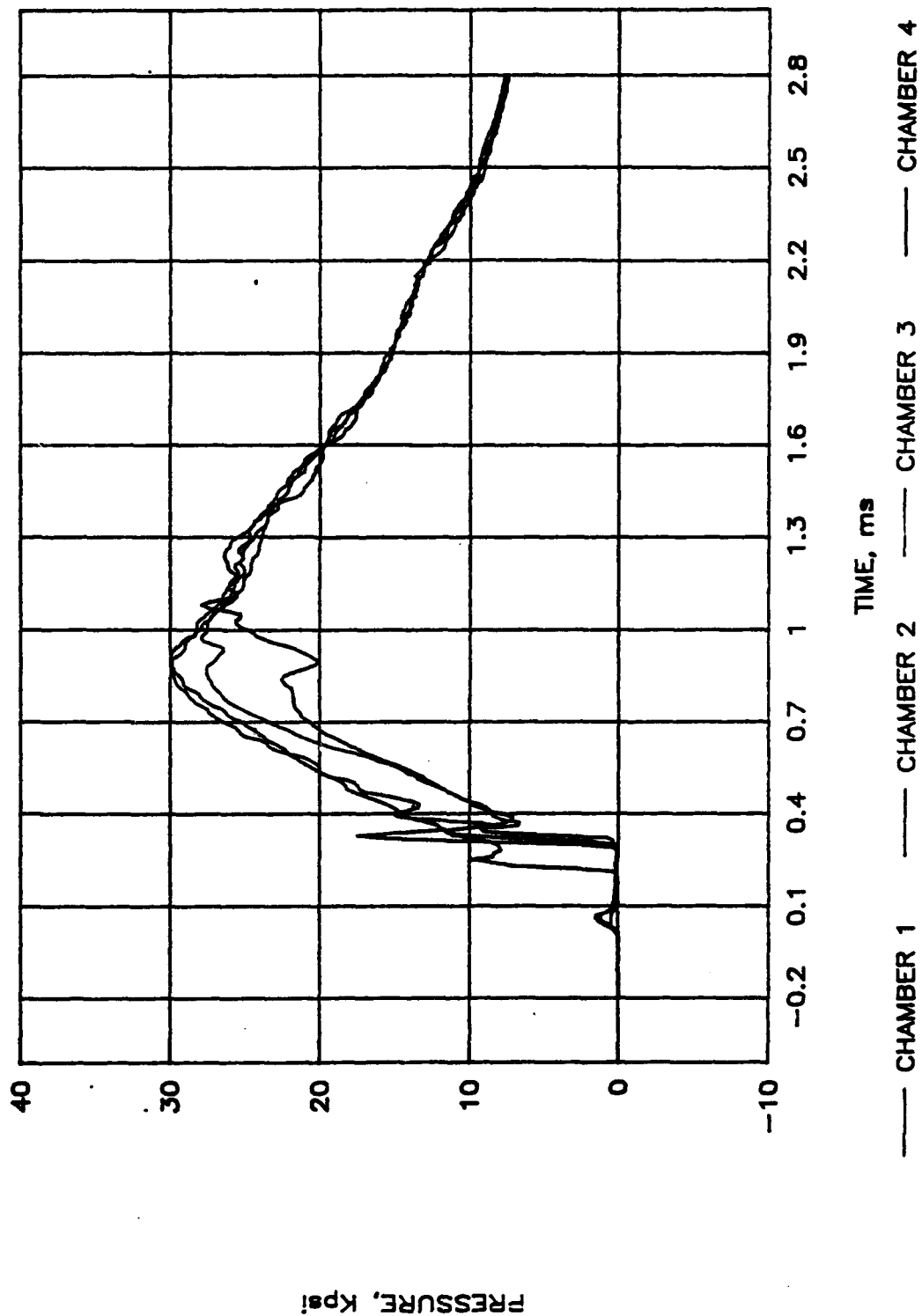
ALL CHAMBERS

OCC15 4-27-93

PRESSURE, Kpsi

TIME, ms

CHAMBER 1 ——— CHAMBER 2 — · CHAMBER 3 ——— CHAMBER 4

181
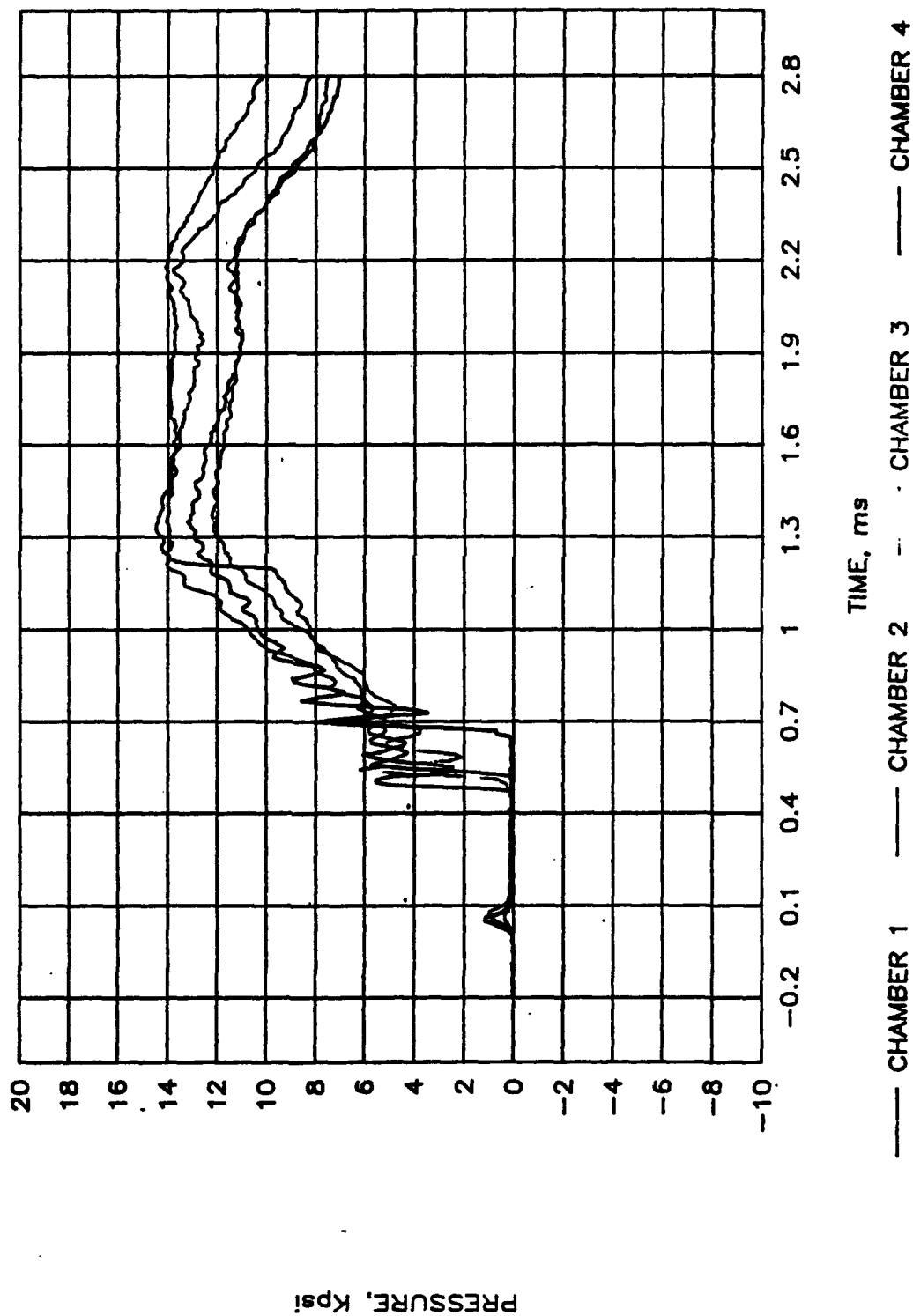
# ALL PRESSURES

## OCC17 4-28-93



TIME, ms

PRESSURE, Kpsi

—— CH 1    —— CH 2    —— CH 3    —— CH 4    —— TUBE ENT    —— MID TUBE

182

Shot OCC01

Propellant Consumed (g) vs Time (ms)

Shot OCC02

Propellant Consumed(g) vs Time(ms)
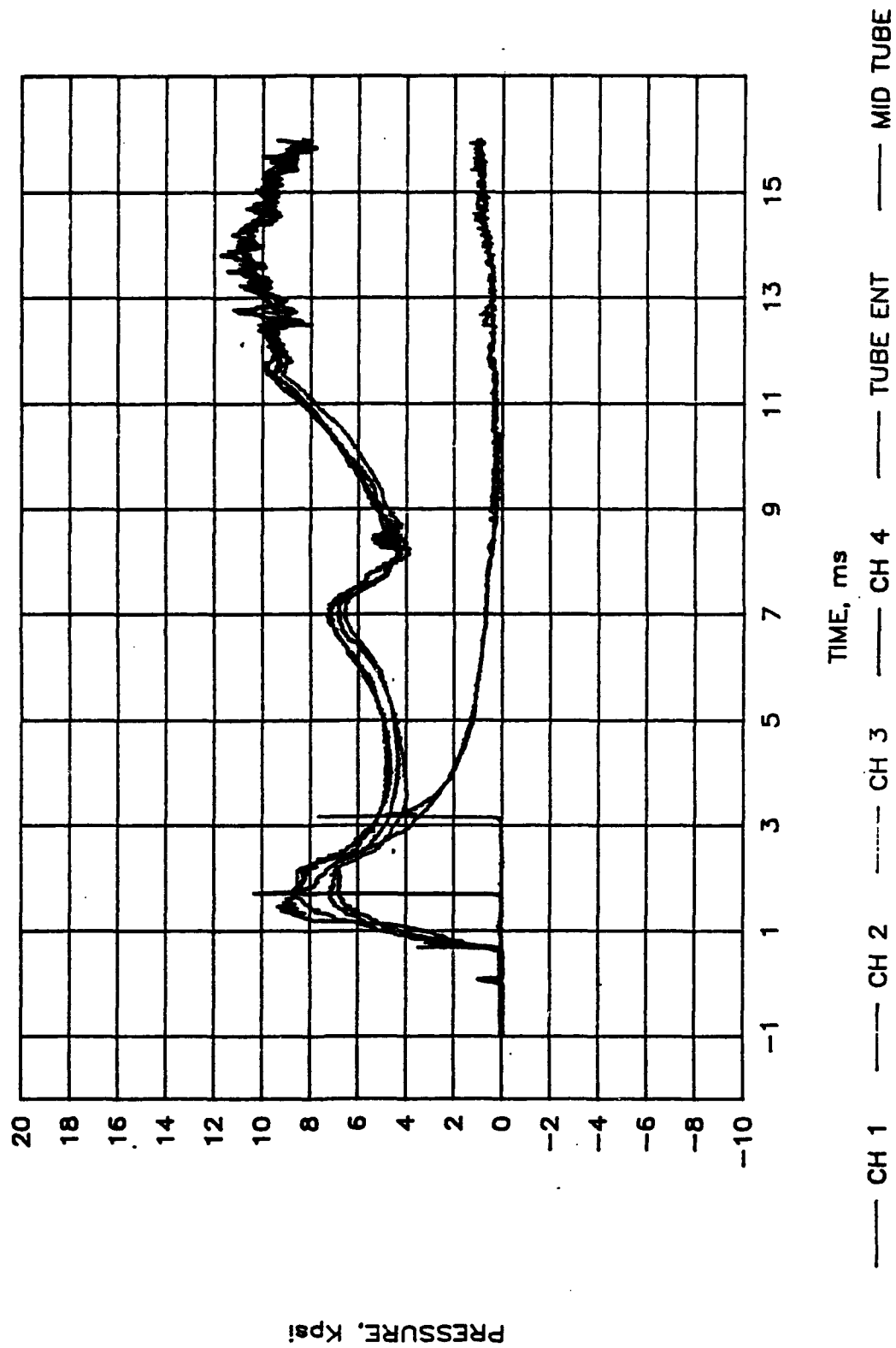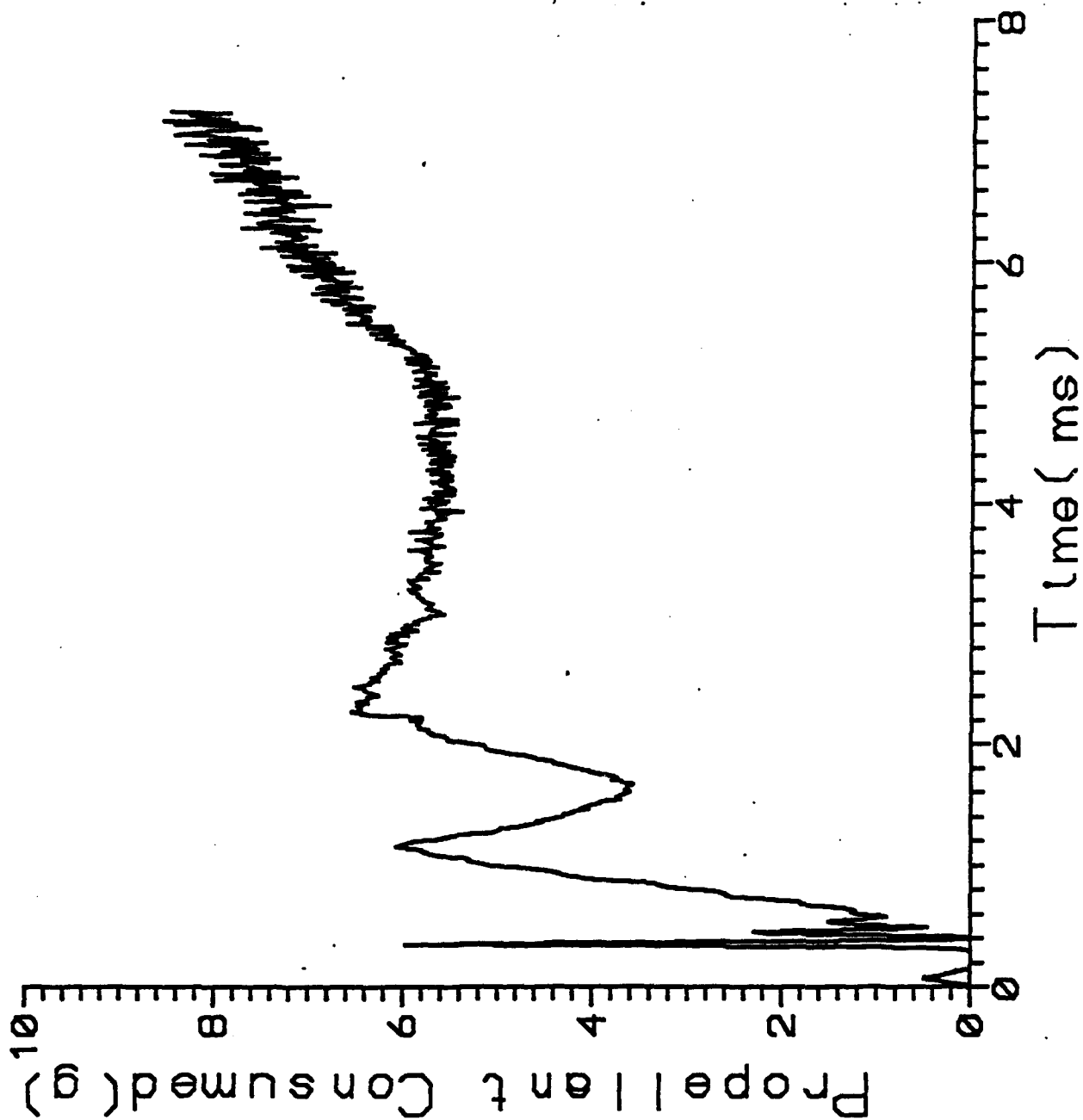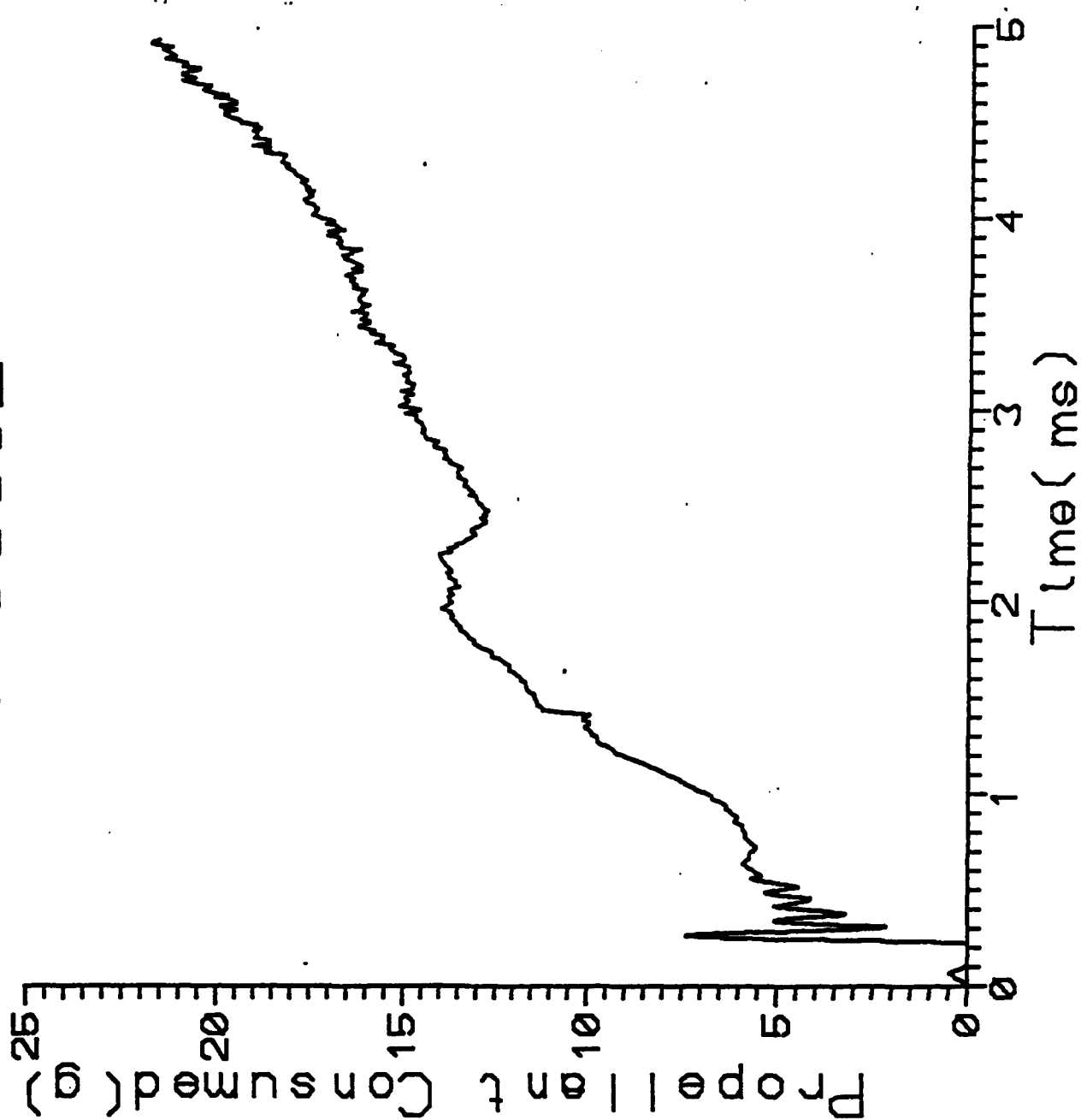
# Evidence Concerning Plasma Enhanced Erosive Burning

- **For**
  - Shape of large residual grains
  - Smooth pt and inverse cp traces
  - Higher than predicted pressure and velocity

- **Against**
  - residue
  - Some cracking in larger grains

- **More data will be obtained in the at least six remaining shots**

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# DROPLET ENTRAINMENT AND BREAKUP
# BY SHEAR FLOWS*

Kenneth K. Kuo and F. Bill Cheung

(Presented in the ETC Modeling Workshop at the Army
Research Laboratory, Aberdeen Proving Ground, MD)

May 12, 1993

# OBJECTIVES

- To evaluate the applicability of existing correlations for describing the entrainment and subsequent breakup of the liquid propellant droplets caused by the discharge of a plasma jet from a plasma generating cartridge.

- To identify the key elements of plasma/liquid propellants interaction that are not fully understood.

- To summarize the findings of this critical review and to define basic research needs for future modeling and diagnostic activities in this subject area.

- To perform a theoretical analysis to provide guidance in the development of a suitable correlation applicable to ETC gun conditions.

# CHARACTERISTIC LENGTH AND VELOCITY SCALES

- ## Two Macro-Length Scales

    $d_h$ — Hydraulic Diameter of the Core Region (Associated with phenomena of the Interfacial Shear Action and Inertia of the Core Flow)

    $\delta$ — Liquid Film Thickness (Associated with Phenomena of Liquid-Film Motion and Induced Surface Wave Form)

- ## One Micro-Length Scale

    $l_{TW}$ — Taylor Wavelength (On the same Order as Ligament or Initial Droplet Size Before Secondary Breakup)

    $$l_{TW} \equiv \left[ \frac{\sigma}{g\left(\rho_f - \rho_g\right)} \right]^{1/2}$$

- ## Two Independent Velocity Scales

    $\begin{cases} V_f & \text{— Bulk Liquid Film Velocity} \\ V_r & \text{— Relative Velocity Between Gas and Liquid} \\ & \quad \text{Phases } (V_r = V_g - V_f) \end{cases}$

    or

    $V_f$ and $V_g$ 189

# OBSERVATIONS OF ENTRAINMENT PHENOMENA

- Similarities exist between the entrainment of liquid propellant by a plasma jet in an ETC gun and entrainment of droplets in two-phase annular mist flow.

- The interface of the two fluids is inherently unstable.

- When $V_r > (V_r)_{critical}$ or $V_f > (V_f)_{critical}$, instabilities set in and grow in the interfacial region.

    - formation of wavy interface and large amplitude roll wave (so-called Kelvin-Helmholtz instability)

    - ligaments and droplets torn off from the interface dynamic interaction

- Critical Conditions for the Onset of Entrainment:



unstable

location of this boundary is a function of fluid properties

stable

$$\frac{V_r \, d_h}{\nu_g}$$

$$\frac{V_f \, \delta}{\nu_f}$$
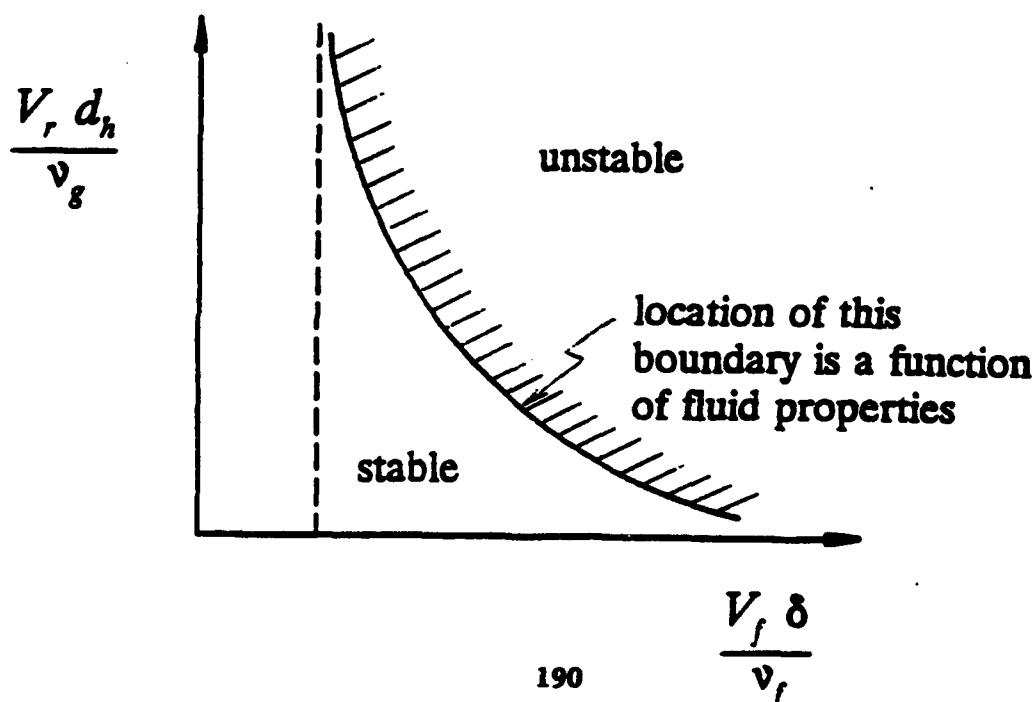
# OBSERVATIONS OF ENTRAINMENT PHENOMENA
## (continued)

- Detailed studies of entrainment mechanism have been performed by Newitt et al. (1954), Hanratty and Hershman (1961), Chung and Murgatroyd (1965), and Ishii and Grolmes (1975).

- In general, entrainment may take place in a number of different ways, depending on the flow situation.

- Hydrodynamic and surface tension forces govern the motion and deformation of the wave crests. Under certain conditions, these forces lead to an extreme deformation of the interface that results in the breakup of a portion of a wave into liquid droplets. The forces acting on the wave crests depend on the flow pattern around them as well as on the shape of the interface.

# RELEVANT ARTICLES ON ENTRAINMENT MECHANISM STUDIES

- "Liquid Entrainment: The Mechanism of Drop Formation from Gas or Vapor Bubbles," Newitt, D. M., Dombrowski, N. and Knelman, F. H., *Tran. Inst. Chem. Engng.*, Vol. 32, p. 244, 1954.

- "Fundamentals of the Hydrodynamic Mechanism of Splitting in Dispersion Process," Hinze, J. O., *AIChE J.*, Vol. 1, p. 289, 1955.

- "Initiation of Roll Wave," Hanratty, T. J. and Hershman, A., *AIChE J.*, Vol. 7, p. 488, 1961.

- "Studies of the Mechanism of Roll Wave Formation on Thin Liquid Films," Chung, H. S. and Murgatroyd, W., *Symp. on Two-Phase Flow*, Vol. 2, Paper A2, Exeter, UK, 1965

- "Prediction of Onset of Entrainment for Liquid Metals," Ishii, M. and Grolmes, M., *Trans. Am. Nucl. Soc.*, Vol. 21, p. 325, 1975

Gas →

Liquid

Type 1
Roll Wave

Gas

Type 2
Wave Undercut

Type 3
Bubble Burst

Type 4
Liquid Impingement

Liquid

Type 5
Liquid Bulge Disintegration
(Counter Current)

Gas
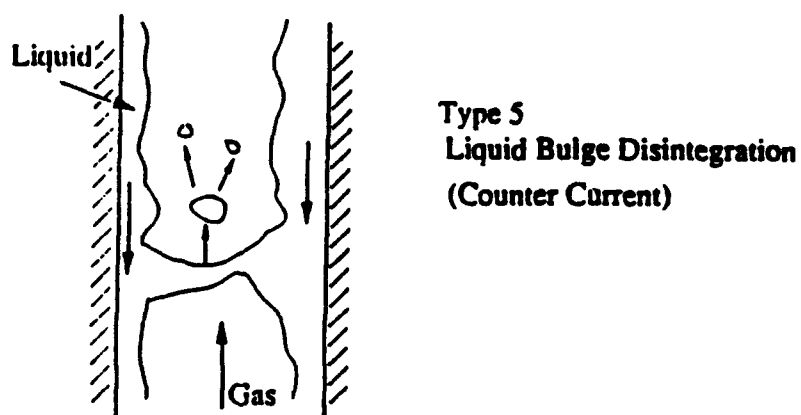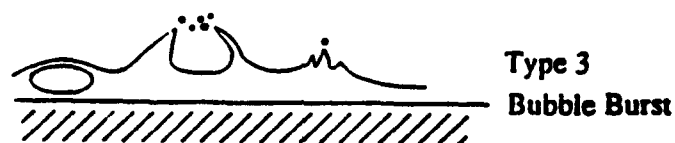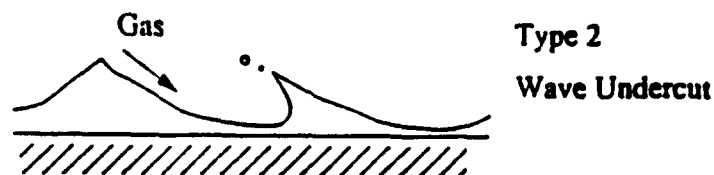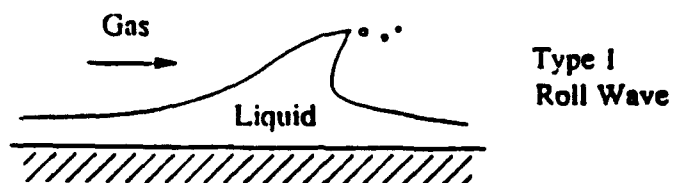
A Schematic Diagram Showing the Five Types of Entrainment Mechanisms

# FIVE BASIC TYPES OF ENTRAINMENT MECHANISMS FOR TWO-PHASE ANNULAR MIST FLOW [ISHII AND GROLMES (1975)]

**ROLL WAVE:**
> The drag force acting on the wave tops deforms the interface against the retaining force of the liquid surface tension. The tops of the large amplitude roll waves are sheared off from the wave crest by the gas flow and then broken into small droplets. (most relevant to ETC gun conditions)

**WAVE UNDERCUT:**
> Entrainment is caused by the undercutting of the liquid film by the gas flow. This mechanism is similar to droplet disintegration by the gas stream. (could also happen in ETC gun condition)

**BUBBLE BURST:**
> Associated with the bursting of gas bubbles. The droplets may be generated by the bubble rising to the surface of a liquid.

**LIQUID IMPINGEMENT:**
> This is caused by the impingement of relatively large liquid droplets to the film interface for production of small droplets.

**LIQUID BULGE DISINTEGRATION:**
> When a counter-current flow reaches the flooding condition, large amplitude waves can emerge from the liquid film and coalesce to from a bridge. Bulged regions of the bridge can then disintegrate into small droplets due to the gas dynamics. (not relevant to ETC gun conditions)

# ONSET OF KELVIN-HELMHOLTZ INSTABILITY

- When both the gas flow and the induced liquid film motion are sufficiently high, the interfacial waves transform into large amplitude roll waves.

- Beyond this critical point, the interfacial shear forces become greater than the surface tension forces, and the onset of entrainment occurs.

LIQUID FILM

$V_f$

$F_\sigma$

$F_i$

GAS CORE

$V_g$

ENTRAINED DROPLET

ROLL WAVE

195
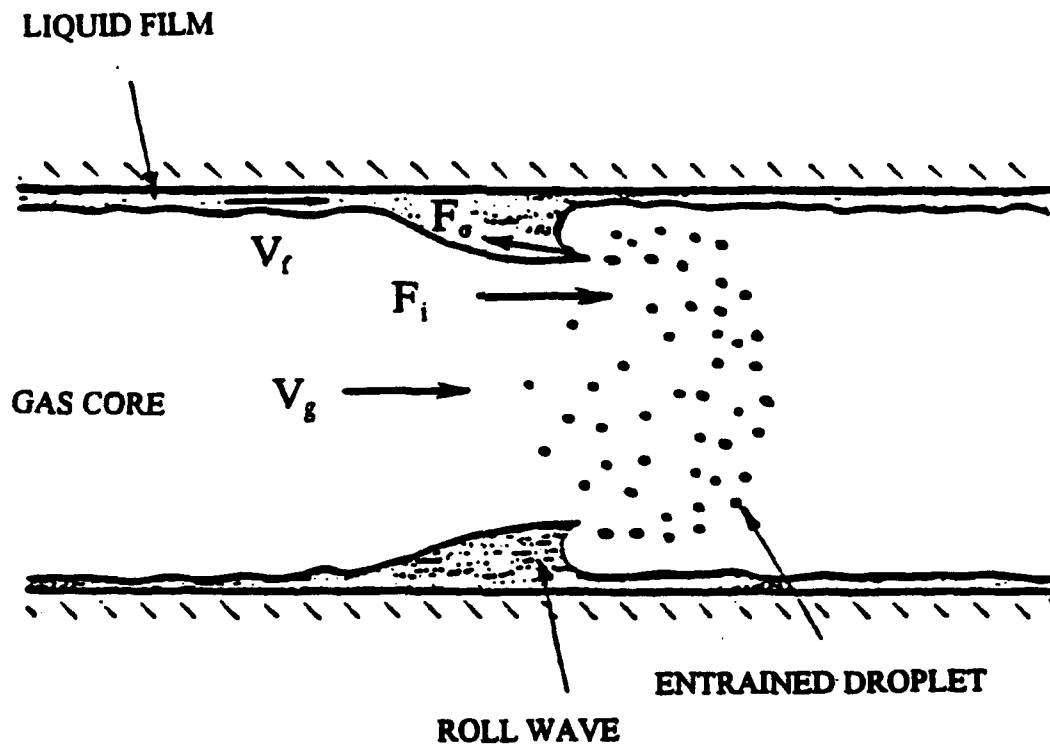
# ONSET OF ENTRAINMENT

- The criterion developed by Ishii and Grolmes (1975) was based upon a force balance at the crest of roll waves. Droplet entrainment starts when

$$F_i \qquad > \qquad F_\sigma$$

$$\begin{bmatrix} \text{interfacial} \\ \text{shear force} \end{bmatrix} \qquad \begin{bmatrix} \text{surface tension} \\ \text{retaining force} \end{bmatrix}$$

- The dimensionless critical superficial gas velocity at the onset of entrainment was found to depend on the film Reynolds number and the viscosity number of the fluids, i. e.

$$(J_g)_{critical} = f(Re_f, N_\mu)$$

$$Re_f \equiv \frac{\rho_f \, j_f \, d_h}{\mu_f}$$

$$N_\mu \equiv \frac{\mu_f}{[\rho_f \, \sigma \, l_{TW}]^{\frac{1}{2}}} = \frac{\mu_f}{\left[ \rho_f \, \sigma \left( \dfrac{\sigma}{g \, (\rho_f - \rho_g)} \right)^{\frac{1}{2}} \right]^{\frac{1}{2}}}$$

where $\rho_f$ and $\mu_f$ are the density and viscosity of the liquid, $d_h$ the hydraulic diameter of the cone, and $j_f$ the superficial velocity of the liquid (including liquid film and droplets).

- $J_g$ is defined as

$$J_g \equiv \frac{j_g}{(\sigma / \mu_f)} \left( \frac{\rho_g}{\rho_f} \right)^{\frac{1}{2}} = \left( \frac{\rho_g \, j_g^{\,2} \, d_h}{\sigma} \right) \left( \frac{\mu_g}{\rho_g \, j_g \, d_h} \right) \left( \frac{\mu_f}{\mu_g} \right) \left( \frac{\rho_g}{\rho_f} \right)^{\frac{1}{2}}$$

$$= \qquad We_g \qquad (Re_g)^{-1} \left( \frac{\mu_f}{\mu_g} \right) \left( \frac{\rho_g}{\rho_f} \right)^{\frac{1}{2}}$$

## ONSET OF ENTRAINMENT (continued)

- For a horizontal two-phase annular flow with $160 < Re_f < 1635$, the criterion of Ishii and Grolmes (1975) gives

$$J_g \geq 11.78 \, N_\mu^{0.8} \, Re_f^{-1/3} \qquad \text{for } N_\mu \leq \frac{1}{15}$$

and

$$J_g \geq 1.35 \, Re_f^{-1/3} \qquad \text{for } N_\mu > \frac{1}{15}$$

- For values of $Re_f$ that are above 1635, a so-called completely rough turbulent regime occurs in which the critical superficial gas velocity becomes independent of the film Reynolds number. According to Ishii and Grolmes (1975), the inception criterion for this flow regime is given by

$$J_g \geq N_\mu^{0.8} \qquad \text{for } N_\mu \leq \frac{1}{15}$$

and

$$J_g \geq 0.1146 \qquad \text{for } N_\mu > \frac{1}{15}$$

- The inception criterion compares favorably with a large number of experimental data for various types of fluids covering a wide range of the film Reynolds numbers and the viscosity number.

- The inception criterion of Ishii and Grolmes should be applicable to the case of plasma/liquid propellants interaction provided that fluid properties are known.
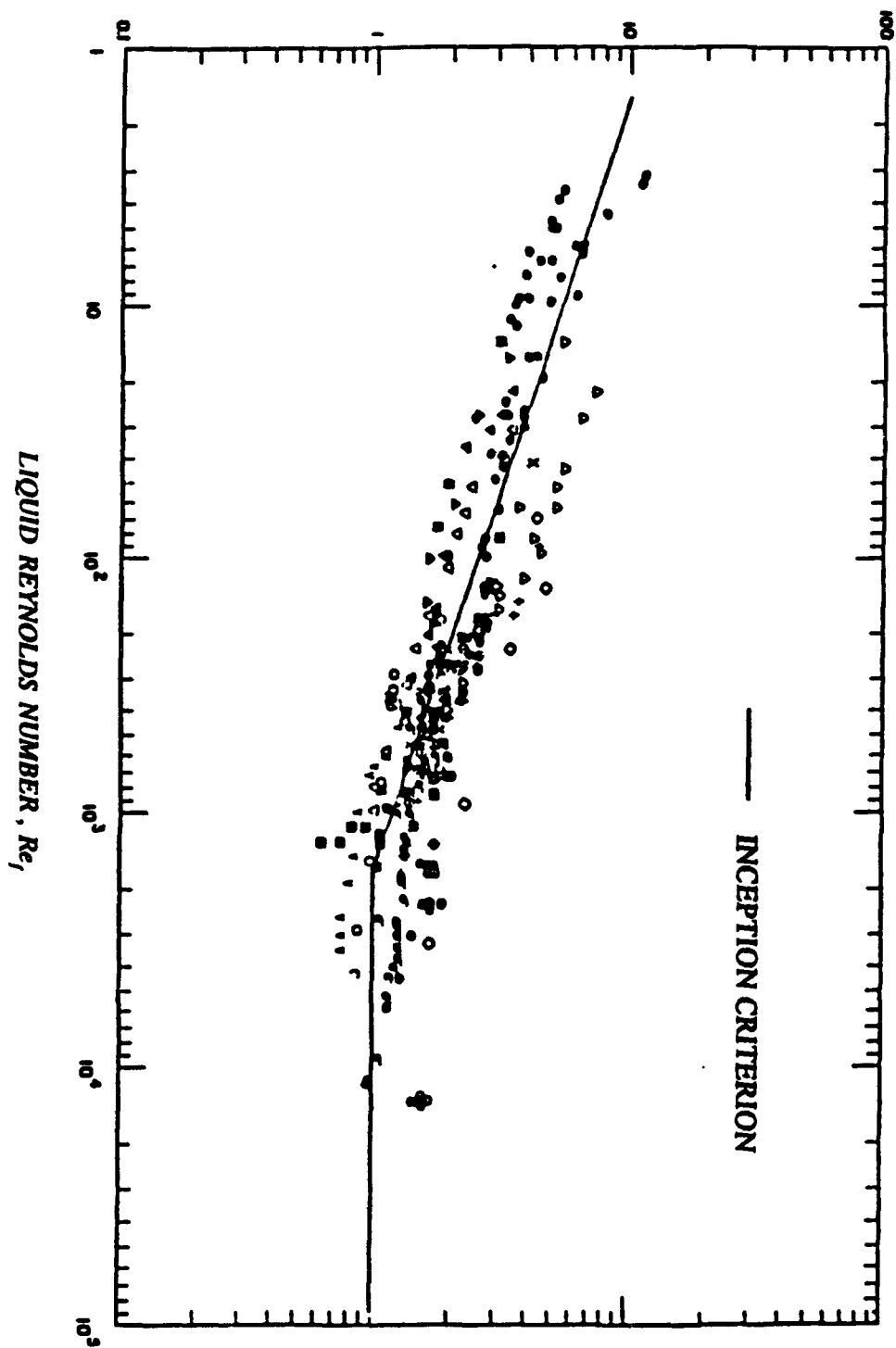
Comparison of the Inception Criterion of Ishii and Grolmes with Data

# METHODS FOR MEASURING THE FRACTION
# OF LIQUID MASS FLUX ENTRAINED
# IN THE GAS CORE

- **Local Probe Measurements**

  — To determine the axial liquid mass flux at the location of the sampling probe.

  — Used with limited success by Wicks and Dukler (1960), Magiros and Dukler (1961), Wallis (1962), Steen and Wallis (1964), Cousins et al. (1965), Gill and Hewitt (1968), and Yablonik and Khaimov (1972).

  — Measurement along the centerline with the assumption that the mass flux is radially uniform.

- **Liquid Film Flow Measurements**

  — Flow rate determined by removing liquid film completely from the test section.

  — This method, which eliminates those uncertainties associated with the local probe measurement, is probably a more accurate measurement technique.

  — Successfully employed by a number of investigators including Paleev and co-workers (1962, 1966), Cousins and Hewitt (1968), Petrovichev et al. (1971), and Ishii and Mishima (1981).

# ENTRAINMENT CORRELATIONS

- **Purely Empirical Approach**

    - Wicks and Dukler (1960)

    - Minh and Huyghe (1965)

    - Paleev and Filipovich (1966)

    - Wallis (1968)

- **Semi-Empirical Approach Based Upon Mechanistic Models**

    - Hutchinson and Whalley (1973)

    - Dallman, Laurinat, and Hanratty (1984)

    - Ishii and Mishima (1989)

# ENTRAINMENT CORRELATION OF WICKS AND DUKLER (1960)

- Developed a correlation that relates the entrainment parameter, R, to the Martinelli parameter X, i. e.

$$R = R(X)$$

- Entrainment Parameter:

$$R \cong \frac{We_c \, (j_f/j_g)}{(dP/dz)_g} \, W_d$$

where $W_d$ is the liquid drop mass flow rate, and $We_c$ the critical Weber number defined in terms of the film thickness $\delta$ by

$$We_c \cong \frac{\rho_g \, v_g^2 \, \delta}{\sigma}$$

where $v_g$ is the velocity of the gas phase.

- Martinelli Parameter

$$X \cong \left[ \frac{(dP/dz)_f}{(dP/dz)_g} \right]^{1/2}$$

where quantities in the numerator and denominator represent the single-phase pressure drops which would exist if each phase flowed alone.

- Two Major Drawbacks

    - The dependence of the entrainment on various controlling factors is hidden by the use of the Martinelli parameter.

    - The correlation is dimensional which severely limits the range of applicability.

# ENTRAINMENT CORRELATION OF MINH AND HUYGHE (1965)

- Empirical correlation relates the entrained fraction, E, to the gas core momentum, i. e.

$$E = E\left( \bar{\rho}_g \, j_g^2 \right)$$

where $\bar{\rho}_g$ is the homogeneous density of the gas core given by

$$\bar{\rho}_g = \rho_g \left( 1 + \frac{\rho_f \, j_d}{\rho_g \, j_g} \right)$$

where $j_d$ is the superficial velocity of the entrained liquid droplets.

- Entrained Fraction:

$$E = \frac{W_d}{W_f} = \frac{j_d}{j_f}$$

where $W_d$ is the mass flow rate of the droplets and $W_f$ the total liquid mass flow rate including both the liquid film and the droplets.

- Two Major Drawbacks

  - The use of the dimensional parameters results in uncertainties regarding the dependence of the correlation on the fluid properties.

  - The range of applicability is virtually unknown as the effects of many important factors such as the liquid Reynolds number are not included.

# ENTRAINMENT CORRELATION OF PALEEV AND FILIPOVICH (1966)

- The shortcoming in the Minh and Huyghe correlation (1965) was eliminated by introducing a dimensionless gas flux* in correlating the entrained fraction in the following form.

$$\frac{W_{ff}}{W_f} = 0.985 - 0.44 \log\left[ \frac{\bar{\rho}}{\rho_f}\left(\frac{\mu_g j_g}{\sigma}\right)^2 \times 10^4 \right]$$

where $W_{ff}$ is the mass flow rate of the film and $W_f$ the total liquid flow rate including the film and droplets.

- Entrained Fraction:

$$E = 1 - \frac{W_{ff}}{W_f}$$

- This correlation showed fairly good agreement with a limited number of data.

- Major Drawback

  - The range of applicability is not well defined as the important effects of the hydraulic diameter and the Reynolds number were not included.

---

*  The dimensionless gas flux is very similar to $J_g$ used in the onset of entrainment.

# ENTRAINMENT CORRELATION OF WALLIS (1968)

- In an effort to improve the correlation of Paleev and Filipovich (1966), Wallis introduced a modified dimensionless gas flux ($\pi$) by replacing the liquid viscosity by the gas viscosity in the Paleev and Filipovich correlation, i. e.

$$E = E\,(\pi)$$

where

$$\pi = \left( \frac{V_g\, \mu_g}{\sigma} \right) \left( \frac{\rho_g}{\rho_f} \right)^{\frac{1}{2}}$$

- Major Drawbacks

  - The range of applicability is not well defined.

  - The dimensionless gas flux is not general enough to account for the effect of fluid properties.

# ENTRAINMENT CORRELATION OF HUTCHINSON AND WHALLEY (1973)

- Proposed a mechanistic model to correlate the rates of entrainment and deposition of droplets to the liquid film.

- The deposition rate is taken to be a linear function of the droplet concentration in the gas core, i. e.,

$$\dot{D} = k\,C$$

where k is the mass transfer coefficient.

- The entrainment rate is considered proportional to the equilibrium concentration, i. e.

$$\dot{E} = k\,C_e$$

The equilibrium concentration is correlated in a functional form given by

$$C_e = C_e\left(\frac{\tau_i\,\delta}{\sigma}\right)$$

where $\tau_i$ is the interfacial shear of the two-phase flow and $\delta$ the liquid film thickness.

- Major Drawbacks

  - It is difficult to accurately determine the equilibrium concentration. The data for this quantity showed considerable scattering, sometimes up to more than an order of magnitude.

  - In order to estimate the entrainment, two different correlations, i. e., one for the entrainment rate and the other for the deposition rate, need to be employed. Any error in determining the deposition would add to the error associated with the entrainment rate.

  - Conceptually, the entrainment rate is not dictated by the equilibrium concentration.

# ENTRAINMENT CORRELATION OF DALLMAN, LAURINAT AND HANRATTY (1984)

- Conducted an experimental study of horizontal annular two-phase flow using air and water.

- The amount of liquid entrained in the gas flow is assumed to be governed by a dynamic balance between the rate of atomization of the liquid film and the rate of deposition of droplets from the gas core.

- The rate of deposition of liquid droplets was considered to vary linearly with the concentration of the droplets whereas the rate of atomization of the liquid film was assumed to vary linearly with the liquid film flow rate.

- Entrainment Correlation Developed:

$$\frac{E}{E_m} = \frac{A\left[(d_h - 2\delta)\,\rho_g^{1/2}\,\rho_f^{1/2}\,v_g^3\right]^{1.5}}{1 + A\left[(d_h - 2\delta)\,\rho_g^{1/2}\,\rho_f^{1/2}\,v_g^3\right]^{1.5}}$$

where A is a dimensional constant having the value of $3.6 \times 10^{-8}$ in SI unit and $E_m$ the maximum entrainment fraction. The latter quantity is given by

$$E_m = 1 - \frac{(W_{ff})_c}{W_f}$$

where $(W_{ff})_c$ is the so-called critical film flow rate.

- Critical Film Flowrate

  - The critical film flow rate has been determined by Dallman et al. (1984) as a function of the ratio between the droplet mass flow rate and the mass flow rate of the gas.
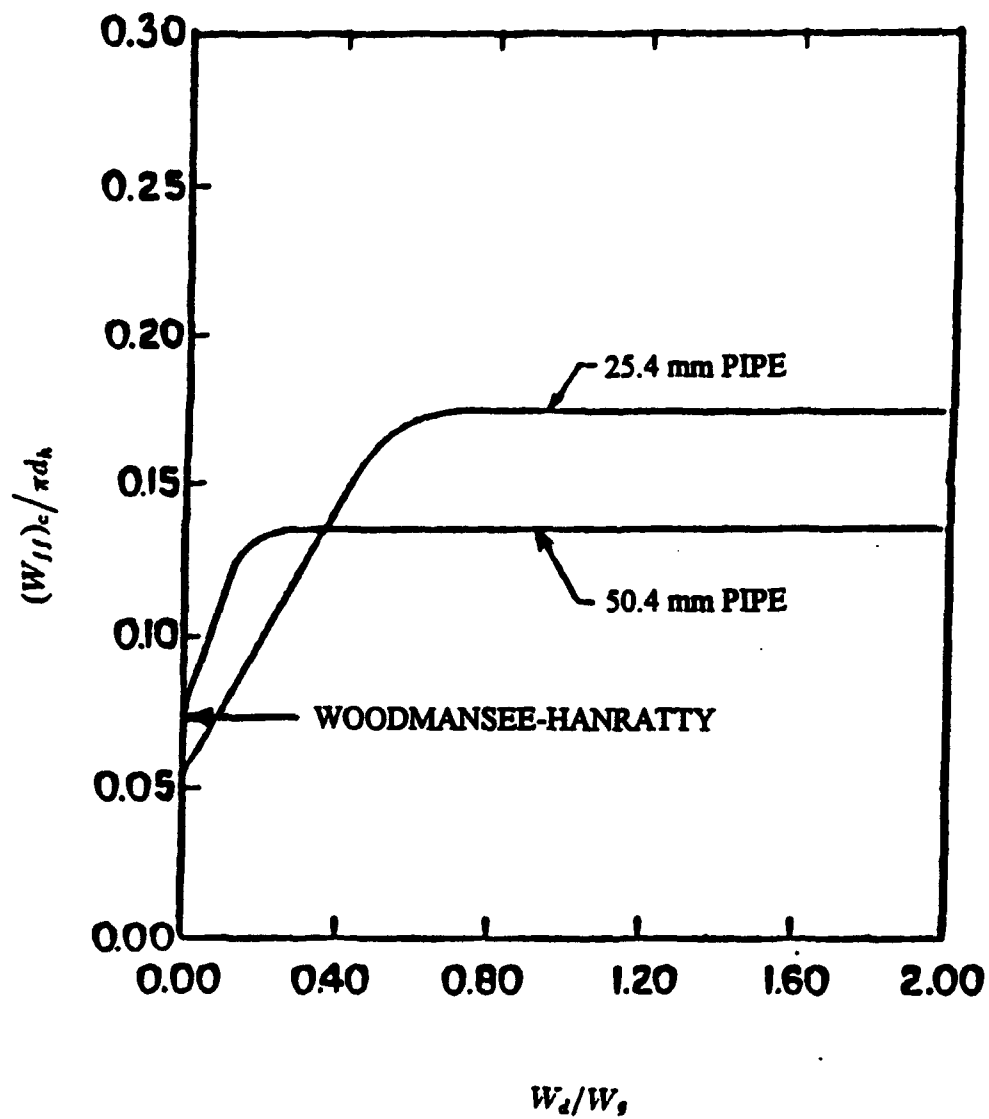
Variation of the Critical Film Flow Rate with the Mass-Flow-Rate Ratio

# ENTRAINMENT CORRELATION OF DALLMAN, LAURINAT AND HANRATTY (1984)
## (continued)

- **Major Drawbacks:**

  - The correlation is given in dimensional form; thus, the applicability is limited.

  - The effect of fluid properties are not included.

  - While the concept of critical film flow rate is correct, the functional dependence of $(W_{ff})_c$ is generally unknown.

  - The correlation is cumbersome as $E_m$ and $\delta$ are unknown quantities.

# ENTRAINMENT CORRELATION OF ISHII AND MISHIMA
## (1989)

- Based upon the mechanism of roll wave entrainment: The shearing off of roll wave crests was considered to be the dominant mechanism of liquid entrainment.

- Droplet entrainment would result whenever the retaining force of surface tension is exceeded by the interfacial shear force.

- The same forces controlling the onset of entrainment were assumed to control the entrainment itself. However, a modification of the inertia of the gas core flow was made to account for the effect of droplet inertia, since there are many droplets flowing in the gas core.

- Under an equilibrium condition in which the deposition rate exactly balances the entrainment rate, the entrained fraction was correlated in the following form:

$$E = \tanh(7.25 \times 10^{-7}\ \widetilde{We}^{1.25}\ Re_f^{-.25})$$

where $\widetilde{We}$ is an effective gas-phase Weber number defined by

$$\widetilde{We} \equiv \frac{\rho_g\, j_g^2\, d_h}{\sigma} \left( \frac{\rho_f - \rho_g}{\rho_g} \right)^{\frac{1}{3}}$$

- The Ishii and Mishima correlation, which compares favorably with a large number of data , is probably the best correlation available today.

- Unfortunately, the entrained fraction represents the equilibrium value that includes the contribution due to droplet deposition. Thus, this correlation tends to underestimate the actual entrainment rate in the ETC gun environment.

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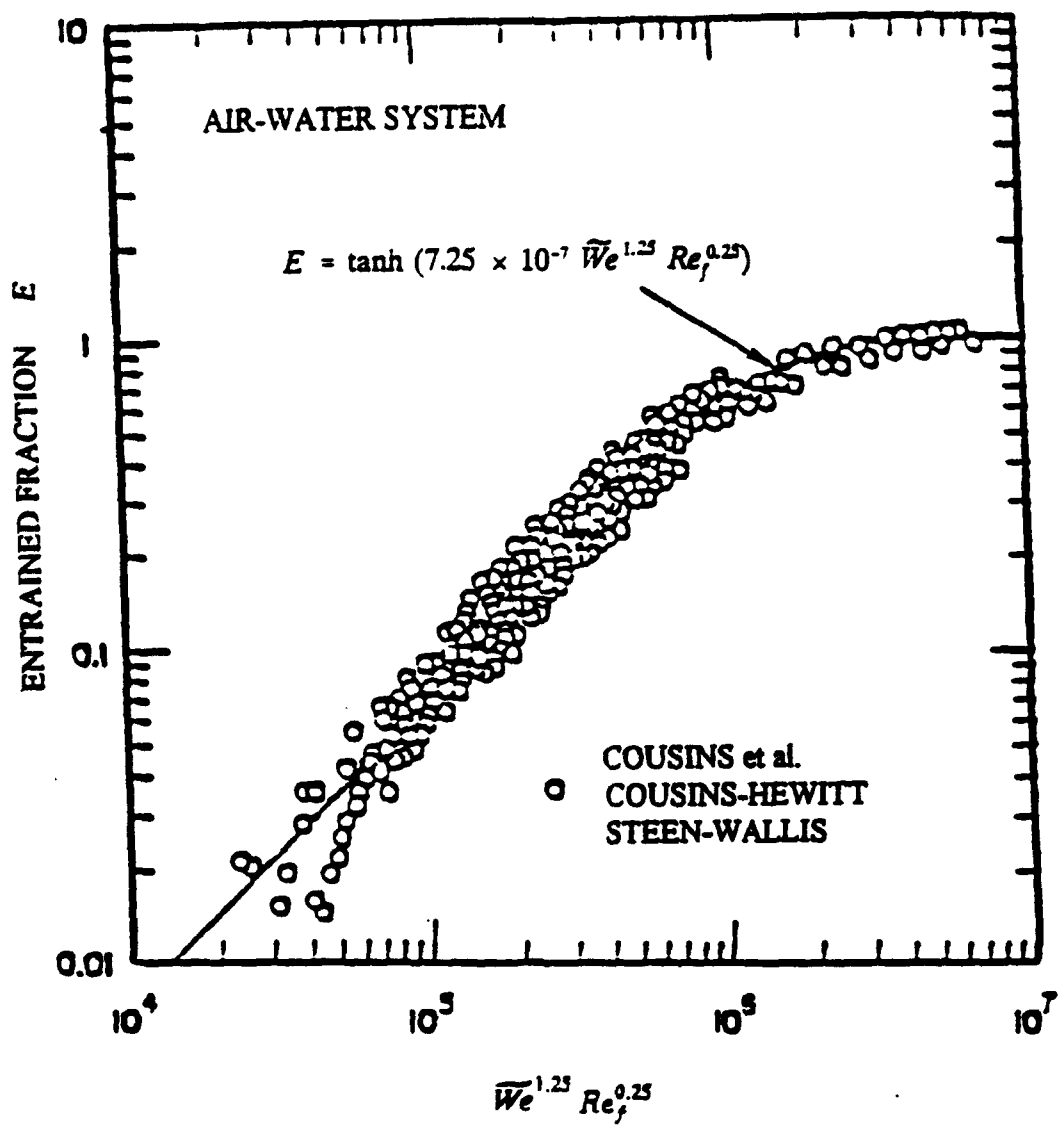
Comparison of the Entrainment Correlation of Ishii and Mishima with Data

# SPECIAL FEATURES OF DROPLET ENTRAINMENT IN AN ETC GUN ENVIRONMENT

- Droplet life times are relatively short due to

    - High rates of heat transfer

    - Evaporation, thermal decomposition, and combustion

    - Secondary breakup to smaller droplets by highly turbulent flow conditions

- The deposition rate is negligible since the droplets have very little chance to return to liquid film before they are totally consumed. The absence of the deposition process in an ETC gun represents a unique feature which is different from all annular two-phase flows studied by previous researchers.

- For ETC guns utilizing piccolo igniters, the phenomena of mixing of plasma and liquid propellants involve two sequential stages.

    1) Development of numerous mini-Taylor cavities and subsequent expansion of cavity sizes.

    2) Merging of mini-Taylor cavities onto a single large cavity.

# RESEARCH NEEDS ON DROPLET ENTRAINMENT

- The single most important element in accurate prediction of the performance of ETC guns is the droplet entrainment rate, since it controls the rate of conversion of chemical energy into propulsive energy.

- A suitable entrainment correlation, excluding the effect of droplet deposition, should be developed for ETC gun application. This can be accomplished by performing an experimental study to measure the rate of entrainment for the case without the effect of deposition.

- In order to develop a realistic model for simulating the mixing phenomena of plasma jets and liquid propellants in ETC guns using piccolo igniters, it is useful to conduct detailed observations of the evolution of mini-Taylor cavities.

# THEORETICAL ANALYSIS OF DROPLET ENTRAINMENT IN AN ETC GUN ENVIRONMENT

- The starting point of the analysis is the selection of an appropriate inception criterion. Since the roll wave mechanism is the prevailing mechanism of entrainment during plasma/liquid propellant interaction in an ETC gun, it is deemed appropriate to adopt the inception criterion of Ishii and Grolmes (1975) in the present analysis.

- Owing to the relatively high velocity of the plasma jet, the plasma/liquid propellant system in an ETC gun is likely to be significantly above the inception criterion. However, there is a potential for the liquid film Reynolds number to be reduced to a critical value as the liquid film thickness decreases. Below this critical $Re_f$, no further entrainment is possible.

# THEORETICAL ANALYSIS OF DROPLET
# ENTRAINMENT IN AN ETC GUN ENVIRONMENT
## (continued)

- An upper theoretical limit for the entrained fraction may thus be determined by assuming that the liquid film flow rate is given by the critical condition for the onset of entrainment:

$$(Re_f)_c^{1/3} = 11.78 \, N_\mu^{0.8} \left( \frac{\sigma}{\mu_f \, j_g} \right) \left( \frac{\rho_f}{\rho_g} \right)^{1/2}$$

where $(Re_f)_c$ is now the critical Reynolds number on the critical film flow rate introduced initially by Dallman, Laurinat and Hanratty (1984).

- The critical Reynolds number is defined by

$$(Re_f)_c = \frac{\rho_f \, (j_{ff})_c \, d_h}{\mu_f}$$

where $(j_{ff})_c$ is the critical superficial velocity of the liquid film. The use of this definition in the above equation is equivalent to ignoring the effect of droplets in determining the critical condition.

- In terms of the liquid film Reynolds number $(Re_f)$, the critical superficial velocity of the liquid film is given by

$$(j_{ff})_c = \frac{j_f}{Re_f} \left[ 11.78 \, N_\mu^{0.8} \left( \frac{\sigma}{\mu_f \, j_g} \right) \left( \frac{\rho_f}{\rho_g} \right)^{1/2} \right]^3$$

# THEORETICAL ANALYSIS OF DROPLET ENTRAINMENT IN AN ETC GUN ENVIRONMENT
## (continued)

- Following the conventional definition, the entrained fraction, E, can be expressed in terms of the superficial velocities of the total liquid (including the liquid film and the entrained droplets) and the liquid film alone, i. e.,

$$E = \frac{j_d}{j_f} = \frac{j_f - j_{ff}}{j_f} = 1 - \frac{j_{ff}}{j_f}$$

- The upper limit of the entrained fraction is given by

$$E_{up} = 1 - \frac{(j_{ff})_c}{j_f}$$

After substituting the expression of $(j_{ff})_c$ into the above equation, $E_{up}$ can be expressed as

$$E_{up} = 1 - \frac{1}{Re_f} \left[ 11.78 \ N_\mu^{0.8} \left( \frac{\sigma}{\mu_f j_g} \right) \left( \frac{\rho_f}{\rho_g} \right)^{1/2} \right]^3$$

- Theoretically, the actual entrainment during the mixing of plasma and liquid propellants in an ETC gun should be bounded by the above upper limit and the lower limit given by Ishii and Mishima (1989), i. e.

$$(E)_{IM} < E < E_{up}$$

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# THEORETICAL ANALYSIS OF DROPLET
# ENTRAINMENT IN AN ETC GUN ENVIRONMENT
## (continued)

- From the above equations, a functional form can be postulated for the actual entrained fraction as

$$E = 1 - B \ Re_f^{-1} \ N_\mu^{2.4} \left( \frac{\sigma}{\mu_f \, j_g} \right)^3 \left( \frac{\rho_f}{\rho_g} \right)^{3/2}$$

  where B is a coefficient that needs to be determined experimentally.

- In view of the fact that the critical superficial velocity of the liquid film represents the lower limit of the liquid film flow, the value of B should be bounded by

$$B \geq 1.635 \times 10^3$$

- In terms of the dimensionless characteristic gas velocity as

$$J_g = j_g \left( \frac{\mu_f}{\sigma \sqrt{\rho_f / \rho_g}} \right)$$

  a more general expression for the entrained fraction can be postulated. This is

$$E = 1 - B \ N_\mu^a \ Re_f^b \ J_g^c$$

- Based upon the preceding physical arguments, the values of the exponents should be approximately equal to: $a = 2.4$, $b = -1$, and $c = -3$. Experimental data to be obtained in the proposed experiments will be used to obtain a final expression for the entrainment correlation.

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# ENTRAINED DROPLET SIZE DISTRIBUTION

- In an ETC gun environment, the chemical reactions that are directly responsible for the transfer of chemical energy to propulsive energy are controlled not only by the entrainment rate but also by the entrained droplet size distribution.

- In an ETC gun chamber, the majority of droplets are generated by entrainment and not by secondary breakup mechanisms. Examples of secondary breakup are turbulence eddy-induced breakup and particle/particle collision generated breakup.

- The size distribution should be governed by the process of the droplet entrainment based on shearing off of the roll waves.

- Studies of droplet sizes have been performed by Hinze (1955), Hass (1964), Wicks and Dukler (1966), Cousins and Hewitt (1968), Tatterson et al. (1977), and Kataoka, Ishii, and Mishima (1983).

- A correlation of droplet size distribution, which could be applied to the interior ballistic processes of an ETC gun, was obtained by Kataoka, Ishii, and Mishima (1983).

# DROPLET SIZE CORRELATION BY TATTERSON DALLMAN AND HANRATTY (1977)

- An experimental study was performed to measure the entrained droplet size in an annular two-phase flow using a log-normal distribution function to simulate the droplet size distribution:

$$We(d_{vm}) = 0.106 \, Re_g^{1.1} \left( \frac{\mu_g^2}{d_h \, \sigma \, \rho_g} \right)^{1/2}$$

  where $\mu_g$ is the gas viscosity, $Re_g$ the gas Reynolds number, and $We(d_{vm})$ the characteristic Weber number based on the volume median diameter.

- The gas Reynolds number and the characteristic Weber number are defined respectively by

$$Re_g = \frac{\rho_g \, j_g \, d_h}{\mu_g} \quad and \quad We(d_{vm}) = \frac{\rho_g \, j_g^2 \, d_{vm}}{\sigma}$$

  where $d_{vm}$ is the volume median diameter. Physically, $d_{vm}$ is defined such that droplets having diameters greater than the volume median diameter would occupy exactly half of the total droplet volume in the gas core.

- Major Drawback:

    Their assumption of a potential flow is not strictly valid for two-phase annular-mist flow with a highly turbulent gas core. As a result, the correlation of Tatterson et al. does not compare favorably with experimental data over a wide range of gas Reynolds number.

# DROPLET SIZE CORRELATION BY KATAOKA ISHII AND MISHIMA (1983)

- A mechanistic model was developed that was based on the mechanism of shearing off of the roll-wave crest for generation of liquid droplets by a viscous shear flow. The potential flow assumption employed in the standard Weber number criterion was eliminated in developing the model development.

- By incorporating the mechanistic model with test data, Kataoka, Ishii, and Mishima (1983) successfully derived a correlation for deducing the volume median diameter from the Weber number

$$We(d_{vm}) = 0.028 \, Re_f^{-1/6} \, Re_g^{2/3} \left( \frac{\rho_g}{\rho_f} \right)^{-1/3} \left( \frac{\mu_g}{\mu_f} \right)^{2/3}$$

- In terms of the characteristic Weber number, the volume median diameter is given by

$$d_{vm} = \frac{\sigma \, We(d_{vm})}{\rho_g \, j_g^2}$$

The above expression correlates the experimental data of volume median diameter within $\pm$ 40% errors.

$$We(d_{vm}) = 0.028\ Re_f^{-1/6}\ Re_g^{2/3} \left( \frac{\rho_g}{\rho_f} \right)^{-1/3} \left( \frac{\mu_g}{\mu_f} \right)^{2/3}$$

△ WICKS-DUKLER
□ COUSINS-HEWITT
✕ LINDSTED et al.

+40%

−40%

$$Y = Re_f^{-1/6}\ Re_g^{2/3} \left( \frac{\rho_g}{\rho_f} \right)^{-1/3} \left( \frac{\mu_g}{\mu_f} \right)^{2/3}$$
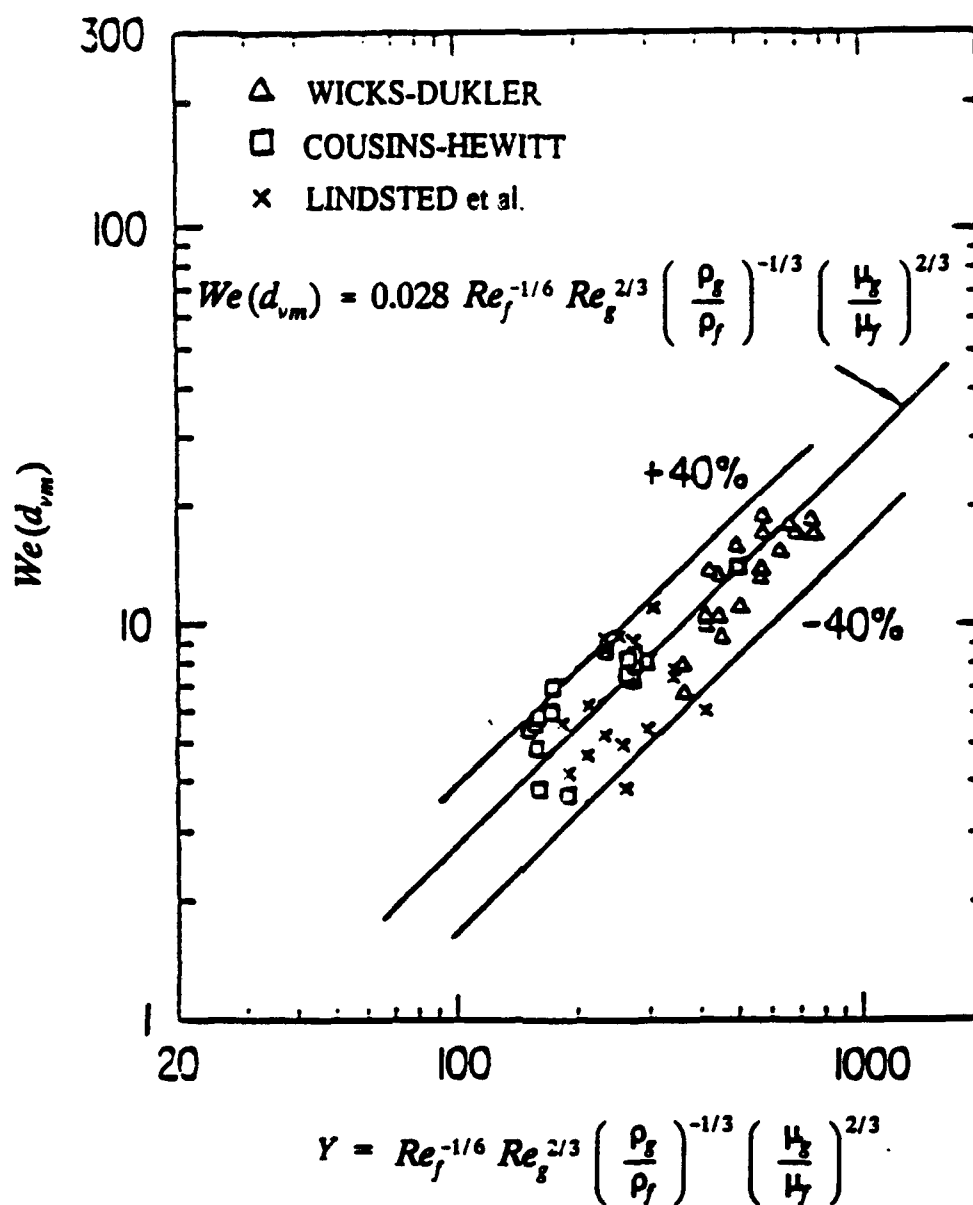
Correlation of the Volume Median Diameter by Kataoka, Ishii and Mishima

# DROPLET SIZE CORRELATION BY KATAOKA ISHII AND MISHIMA (1983)
## (continued)

- The mean values of the data on drop size distribution were fitted by Kataoka, Ishii, Mishima (1983) to the upper limit log-normal distribution:

$$\frac{d\,\Delta}{dy} = -\frac{\xi}{\sqrt{\pi}}\,\exp\left[-(\xi y)^2\right]$$

where $\Delta$ is the volume fraction oversize defined as the volume fraction of droplets having a diameter larger than a given diameter, d.

- In the above equation, $\xi$ is a distribution parameter and $y$ is defined in terms of the maximum diameter $d_m$ and volume mean diameter $d_{vm}$ as

$$y = \ln\left[\frac{k\,d}{(d_m - d)}\right] \quad and \quad k = \frac{(d_m - d_{vm})}{d_{vm}}$$

- Based upon the experimental results, the values of $\xi$ and $k$ were found to be $\xi = 0.884$ and $k = 2.13$ whereas using the upper limit log-normal distribution, the maximum diameter was related to the volume mean diameter by

$$d_m = 3.13\,d_{vm}$$

# DROPLET SIZE CORRELATION BY KATAOKA
## ISHII AND MISHIMA (1983)
### (continued)

● The correlation of drop size distribution developed by Kataoka, Ishii, and Mishima (1983) is probably the most suitable one among the existing correlations for use in simulating the phenomena of mixing of plasma and liquid propellants in the ETC gun environment.

● It is recommended that the correlation be used in future modeling. The reasons are:

— The correlation is based upon a sound physical model, taking full account of key elements involved in the droplet formation process

— The use of the upper limit log-normal distribution function is evidently appropriate for annular-mist flow

— The correlation compares very well with available experimental data on drop size distribution covering a wide range of conditions

— The correlation is easy to use since the primary quantity that needs to be determined is the volume median diameter.

# Electrothermal-Chemical Gun Interior Ballistic Modeling

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Weapons Technology Directorate
Aberdeen Proving Ground, Maryland
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# Interior Ballistic Component Processes

| | LPETC | SPETC |
|---|---|---|
| **Plasma generation:** | Variety of plasma generation concepts. Not dependent on propellant type. Generates little mass; temperatures 10 - 30,000 K. Coupled to combustion chamber. | |
| **Ignition:** | Little or no ignition delay. No detailed information. | |
| **Gas flow and flamespread:** | Similar to bulk-loaded LPG. Moving to higher ullage charge designs. | Appears similar to conventional SP charges. More influence from radial convection & radiation in designs with chamber burst tube. |
| **Combustion: & Mixing** | Complex process. Propellant surface area not well defined. Similar to processes in BLPG. Droplet entrainment & breakup at high shear flows. | Data suggests plasma does not directly affect SP combustion process in a major way. Impact on gas internal energy & pressure. |
| **Expansion:** | Anticipate diminishing plasma influence with increasing projectile travel for breech/chamber injected plasmas. | |

**ARL**

# Appropriate Dimensionality

- **Practical motivation to utilize codes with lowest dimension to obtain desired information**

  - reduce complexity, decrease run time, decrease post processing
  - reduce need for specialized personnel
  - 'user friendly' models needed for the larger ballistics community

- **Lumped parameter IB codes**

  - macroscopic parameters such as max pressure & muzzle velocity
  - mean IB history
  - ETC applications currently require empiricism, especially for liquids

- **quasi 1D, multi-phase, IB codes**

  - axial structure of flamespreading
  - energy, mass & momentum of plasma at various axial locations
  - details of multi-phase flow
  - investigate sources of longitudinal pressure waves

- **2D / 3D, multi-phase IB codes**

  - radial structure of flamespreading
  - influence of turbulence
  - radial structure of plasma in combustion chamber
  - investigate sources of radial, tangential & longitudinal pressure waves
  - detailed interaction of multiple plasma sources
  - influence of complex geometries

# Dimensionality for IB Simulations

| | Plasma | LPETC | SPETC |
|---|---|---|---|
| **0D (Lumped parameter)** | Not generally utilized. | Models available. Require specification of mass generation rate. e.g. as function of injected plasma energy. Closely coupled to experiment. Both 0D & 1D models can be used to simulate experiment, but predictive capability is limited. | Adaptations of existing IB models. Reasonable agreement with experiment using traditional assumptions at modest electrical energy densities & breech plasma capillaries. |
| **1D** | Ideal & nonideal, quasi-steady & transient models provide good agreement with macroscopic measurables. Has been coupled to 2D/3D IB model. | | Adaptations of existing IB models available. Reasonable agreement with experiment. Design of plasma generator (e.g. internal, burst tube.) may have large effect; currently not explicitly modeled. |
| **2D/3D** | Some indications of significant radial structure in capillary. May influence plasma characteristics. Model development underway. | IB process appears to be at least 2D. Macroscopic agreement good. Microscopically complex. Research in turbulence submodels. Uniqueness? | Initial efforts to develop multi-phase, CFD, solid propellant IB models. |

# ETC IB Models

| Model | Description | Status |
|-------|-------------|--------|
| P2SIM | 0D, power systems for electric guns, includes mission scenarios | Complete |
| Plasma | 1D steady state capillary<br>1D transient capillary<br>  - treats metals (In Progress)<br>1D piccolo tube<br>2D capillary | Complete<br>Complete<br><br>In Progress<br>In Progress (SNL) |
| BLAKE-ETC | Thermochemical code, treats electrical energy as a constituent | Complete |
| IBHVG2 -ETC | 0D, EE source term<br>Input power<br>  - coupled to plasma (In Progress) | Complete |
| SPETC | 0D, SP, Determines power pulse for given performance<br>  - optimization (In Progress) | Complete |
| LUMPET | 0D, LP, Arrehenius EOS<br>EE source term | Complete |
| Conpress | 0D, Constant pressure solution, EE source term | Complete |
| XKTC-ETC | 1D, Solid propellant code, EE source term | Complete |
| CRAFT | 1D/2D/3D research code, fundamental physics, state-of-the-art numerics<br>  - gas/gas (Complete)<br>  - gas/liquid (Complete)<br>  - gas/liquid/solid (In Progress) | In Progress |

# Power Model

- **Virtually all electric gun power systems**
- **Includes mission scenarios**
- **Developed by PCRL**
- **Application by P. Tran**



EEF FOLLOW-ON PROGRAM
10kV PFN TESTS #1-10



P2SIM PREDICTION
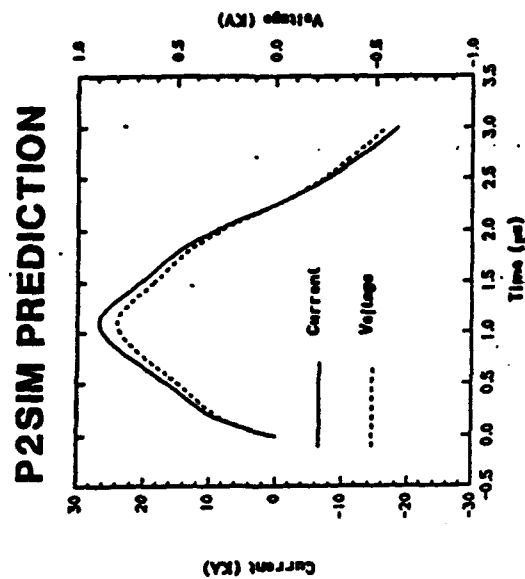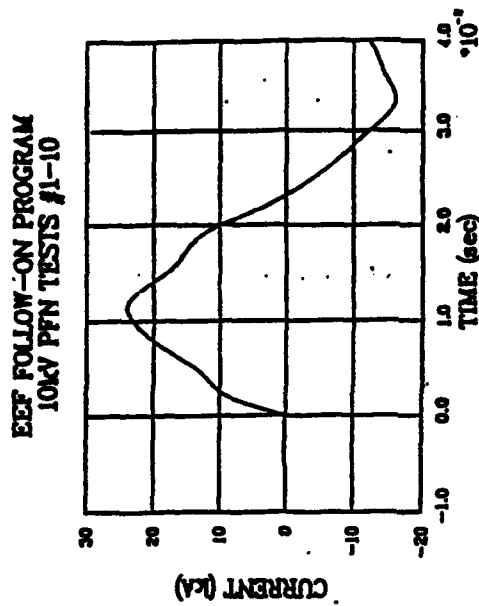
FMC Pulse-Power Module
for 9MJ ET Skid Gun:
Verification Test 1

# Plasma Models

ARL



- **Past Accomplishments:**

  - Develop 1D, steady-state, capillary model for breech-fed mixing chamber

  - Included nonideal effects for relatively high-density, low-temperature plasmas

  - Extended solution to 1D, fully transient case

  - Effected comparison with various sets of experimental data

- **Present Activities:**

  - Develop capability for treating mixture of several different species

    Account for electrode ablation
    Account for fuse vaporization

  - Extend model to treat "piccolo" injector

  - Couple plasma model to 2D, Interior Ballistic, CFD models
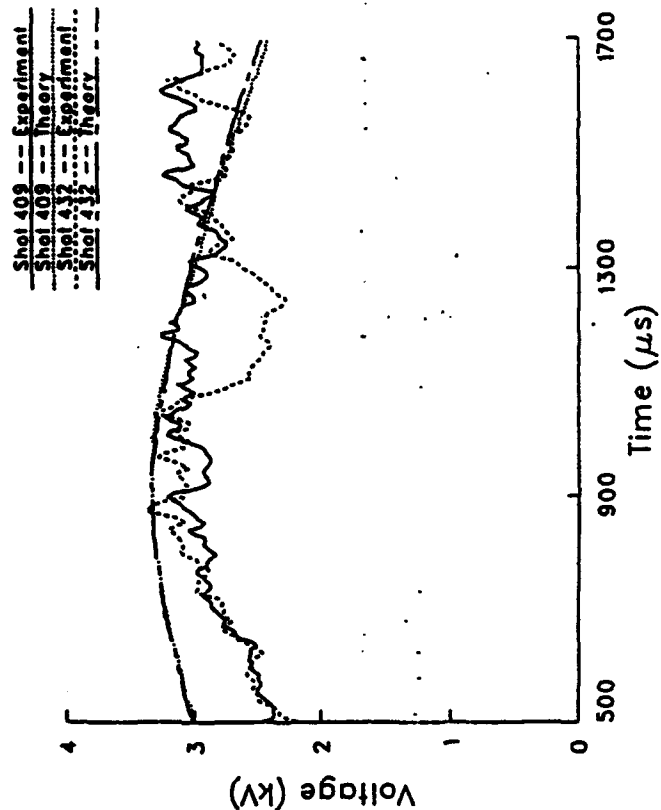
# Status of Plasma Activities



Capillary Injector — Piccolo Extender

- Piccolo
  - Developed 1D, transient model for piccolo extension to breech-fed injector
  - Performing calculations to compare with FMC experimental data
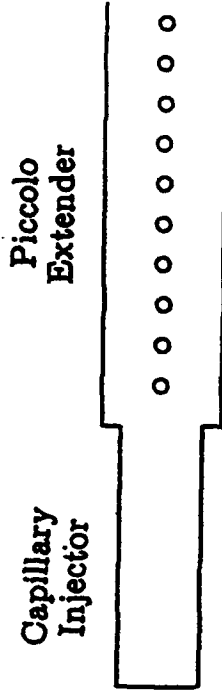
- Coupling to CFD models
  - Isothermal, steady-state, breech-fed plasma code included in CRAFT
  - Coupled calculations performed for FMC and GDLS data

- Mixtures
  - Formulated equations for calculating EOS's and conductivity for arbitrary mixture of C, H, Cu, Al, Fe, O, and N
  - Developed stand-alone code and subroutine for performing calculations
  - Initiated calculations for breech-fed injector accounting for vaporization of Al fuse

* Much of work done in collaboration with SAIC – Atlanta, Ft. Washington

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# Experimental Fixture

ARMY RESEARCH LABORATORY
WEAPONS TECHNOLOGY DIRECTORATE

Bore diameter: 30mm
Chamber volume: 160 cc
Chamber diameter: 3.175 cm
Chamber L/D: 6.15
Travel: 16.1 cm
Projectile mass: 328.8 g

RTV DISK

LEXAN TUBE OUTER WALL

THIN PLASTIC FILM

RTV USED TO
SEAL CHAMBER

65.3 GRAMS OF
PROPELLANT (NO
ANNULAR ULLAGE)

1/4" CAPILLARY

# Ignition Characterstics

- Ignition time delays close for same material ( Average 0.35 ms )
- Plasma driven propellants appear to exhibit reduced variability in ignition

| Shot | Propellant | Ignition delay |
|------|-----------|----------------|
| 1 | LGP1846 | 0.36 |
| 2 | LGP1846 | 0.24 |
| 3 | LGP1846 | 0.28 |
| 4 | LGP1846 | 0.24 |
| 5 | LGP1846 | 0.20 |
| 6 | LGP1846 | 0.17 |
| 8 | N2H4/HN | 0.28 |
| 9 | HAN/DEG/H2O | 0.26 |
| 10 | HAN/DEG/H2O | 0.30 |
| 11 | HAN/DEG/H2O | 0.29 |
| 12 | HAN/NMP/H2O | 0.26 |
| 13 | HAN/NMP/H2O | 0.32 |
| 14 | M43 | 0.24 |
| 15 | M43 | 0.24 |
| 16 | DINA/NC | 0.23 |
| 20 | DINA/NC | 0.25 |

| Shot | Propellant | Ignition delay |
|------|-----------|----------------|
| 17 | RDX/NC/NG | 0.30 |
| 19 | RDX/NC/NG | 0.33 |
| 22 | AN/Cyanoguanidine | 1.68 |
| 23 | AN/MEAN/H2O | 0.27 |
| 24 | AN/MEAN/H2O | 0.30 |
| 25 | AN/5AT/H2O | 0.94 |
| 26 | AN/5AT/H2O | 0.82 |
| 27 | JA2 | 0.24 |
| 28 | JA2 | 0.30 |
| 29 | JA2 - X | 0.23 |
| 30 | JA2 - X | 0.30 |
| 31 | JA2 | 0.27 |
| 32 | JA2 | 0.27 |
| 33 | Compacted CAB | 0.87 |
| 34 | Compacted CAB | 0.12 |
| 35 | Loose CAB | 0.23 |
| 36 | Loose CAB | 0.20 |
| 37 | Loose CAB | 0.16 |
| 38 | Loose CAB | 0.16 |

# Pressurization Rate

- 'Runaway' combustion does not occur
- 120mm tank round: dP/dt = 0.4 MMPa/s
- 155mm artillery round: dP/dt = 0.09 MMPa/s

| Shot | Propellant | Derivative (MMPa/s) |
|---|---|---|
| 1 | LGP1846 | 3.820 |
| 2 | LGP1846 | 3.670 |
| 3 | LGP1846 | 0.134 |
| 4 | LGP1846 | 0.084 |
| 5 | LGP1846 | 0.327 |
| 6 | LGP1846 | 0.121 |
| 8 | N2H4/HN | 0.151 |
| 9 | HAN/DEG/H2O | 0.124 |
| 10 | HAN/DEG/H2O | 0.133 |
| 11 | HAN/DEG/H2O | 0.119 |
| 12 | HAN/NMP/H2O | 0.122 |
| 13 | HAN/NMP/H2O | 0.137 |
| 14 | M43 | 0.117 |
| 15 | M43 | 0.136 |
| 16 | DINA/NC | 0.108 |
| 20 | DINA/NC | 0.153 |

| Shot | Propellant | Derivative (MMPa/s) |
|---|---|---|
| 17 | RDX/NC/NG | 0.129 |
| 19 | RDX/NC/NG | 0.123 |
| 22 | AN/Cyanoguanidine | 0.113 |
| 23 | AN/MEAN/H2O | 0.150 |
| 24 | AN/MEAN/H2O | 0.180 |
| 25 | AN/5AT/H2O | 0.338 |
| 26 | AN/5AT/H2O | 0.272 |
| 27 | JA2 | 0.198 |
| 28 | JA2 | 0.186 |
| 29 | JA2 - X | 0.161 |
| 30 | JA2 - X | 0.183 |
| 31 | JA2 | 0.179 |
| 32 | JA2 | 0.172 |
| 33 | Compacted CAB | 0.075 |
| 34 | Compacted CAB | 0.218 |
| 35 | Loose CAB | 0.119 |
| 36 | Loose CAB | 0.112 |
| 37 | Loose CAB | 0.203 |
| 38 | Loose CAB | 0.228 |

# Closed Chamber Burn R  3

- **Research at ARL in SP combustion with plasma**

  - ETC diagnostic closed chamber/gun fixture
  - Specialized ETC closed chamber data analysis code

- **M5 solid propellant with conventional ignition vs plasma augmented**

  - 50 cc closed chamber data
  - Plasma pulse 1.2 ms, 125 kJ
  - Analyzed using BRLCB

- **Prompt ignition with plasma**

- **In closed chamber plasma does not appear to influence burn rate of SP**

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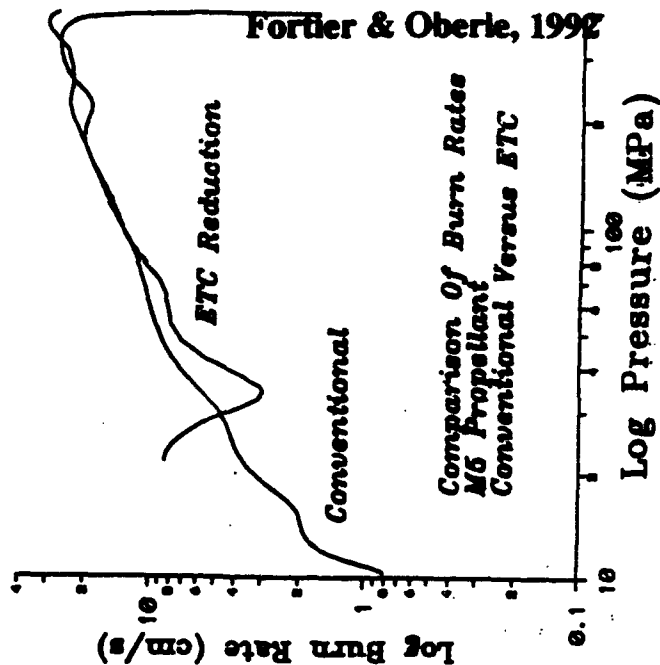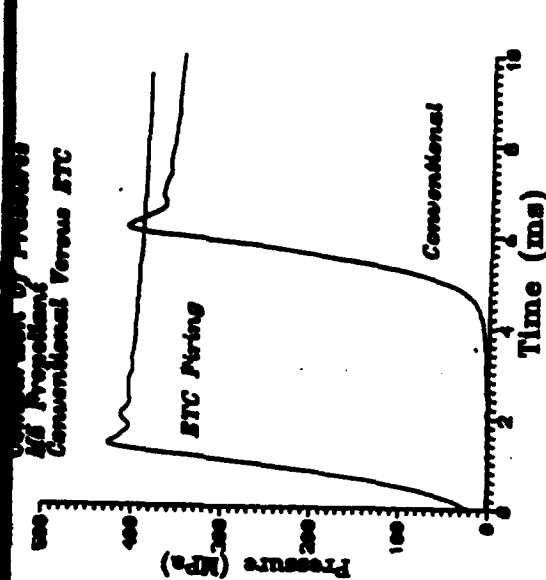
# Experiment OCB14

- **30mm fixture**
  - Chamber volume: 160 cc
  - Propellant mass: 65.3 g
  - Chamber diameter: 3.175 cm
  - Chamber L/D: 6.15
  - Travel: 161 cm
  - Projectile mass: 324.36 g

- **M43 solid propellant**
  - Number of perfs: 7
  - Outer diameter 0.2895 cm
  - Diameter perf: 0.0119
  - Grain length: 0.6197 cm

- **Central ullage tube**

- **Electrical energy**
  - Ramped pulse over 1.9 ms
  - 41.167 kJ

235
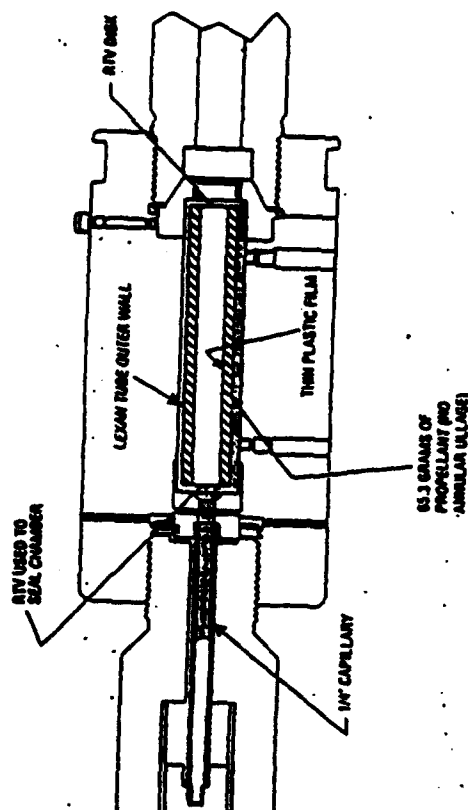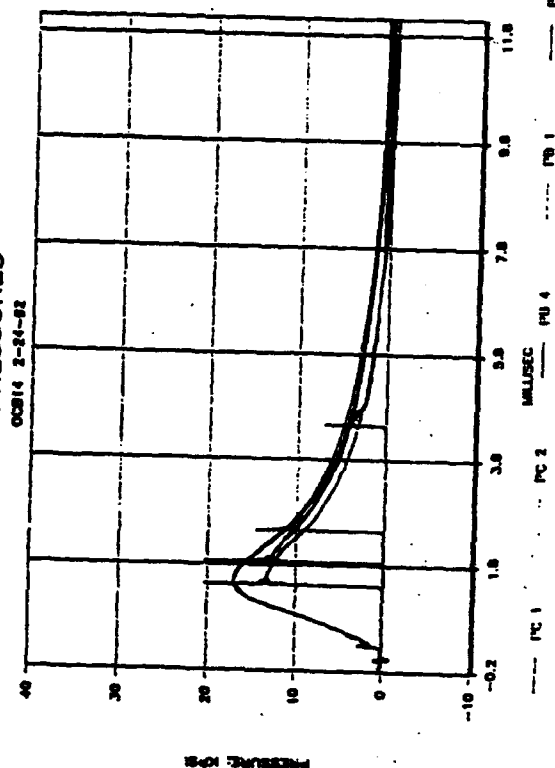
# M43 Burn Rate with Plasma



Burn Rate Comparison
M43 Versus Shot 14 (Star)

M43 Burn Rate

Shot 14 Burn Rate

Log Pressure (MPa)

Log Burn Rate (cm/s)

Comparison Of Burn Rates
M43 Versus Shot 14
100 Microsecond Delay

M43: Solid line
Shot 14: Star

Log Pressure (MPa)

Log Burn Rate (cm/s)

Wren & Oberle, 1993

- **Closed chamber data at ARL**
  - M43, lot IH91H-E00040
  - analyzed using BRLCB

- **Inverse code results**
  - use experimental data to obtain mass burned history
  - use m dot & grain geometry to deduce burn rate using modified BRLCB

- **Delay in plasma**
  - current & voltage measured at rear of capillary
  - assume 0.0 and 100 microsecond delay in energy release in combustion chamber

236
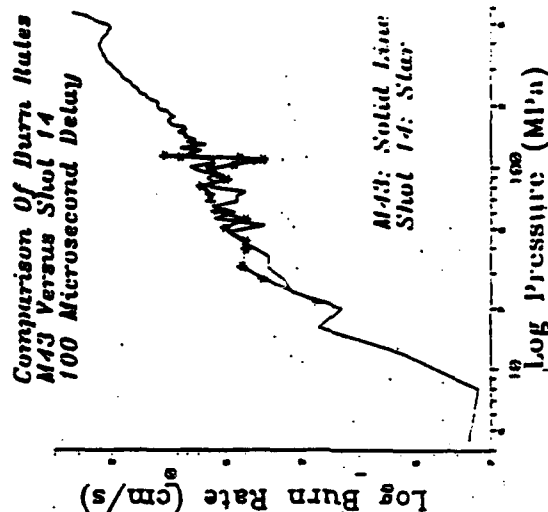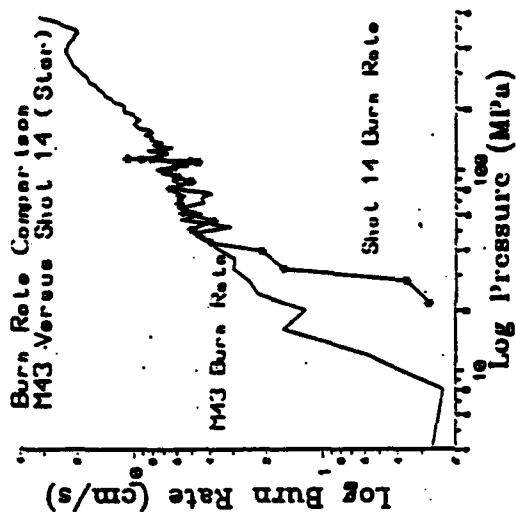
# Shots 160 and 161 from Soreq

Input parameters:

- Bore diameter: 60-mm
- Travel: 3.881 m
- Chamber volume: 2183 cc
- Charge weight: 1.73 Kg
- Propellant: M30, 7perf
- Projectile mass: 1.35 Kg

# Energy vs Time



Energy vs Time
(Shot 160)
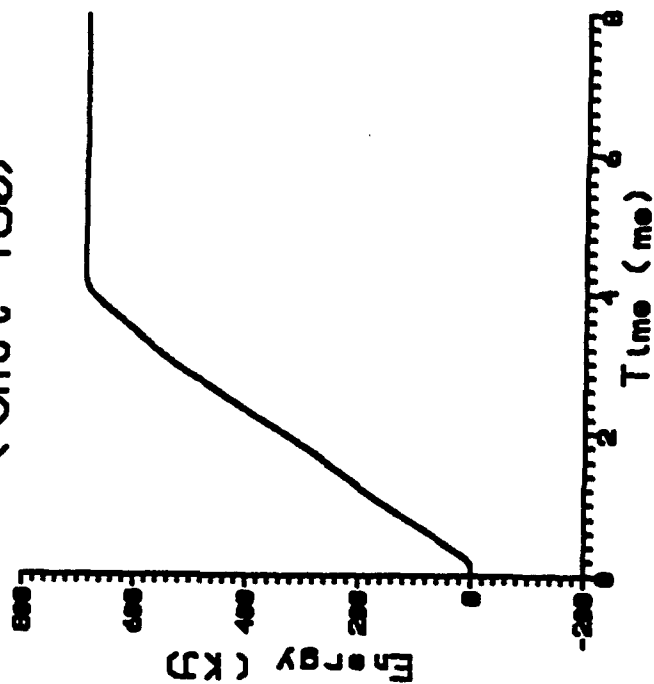
Energy vs Time
(Shot 161)
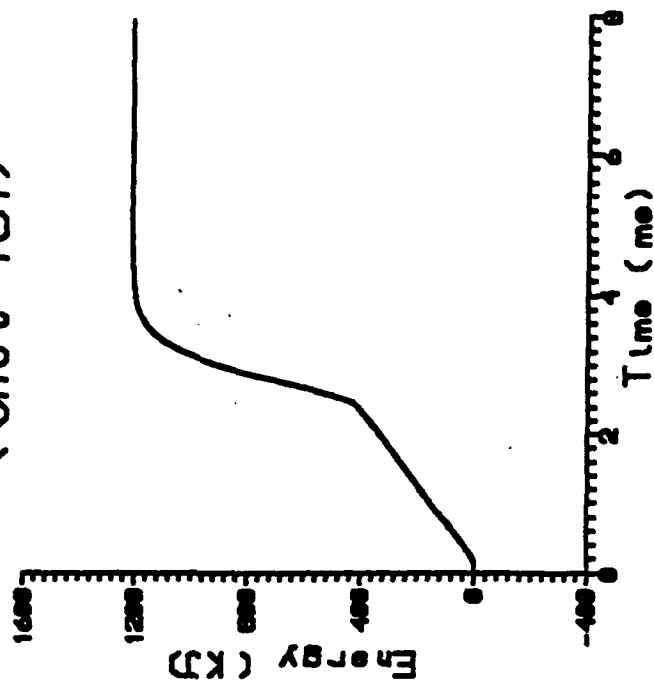
# Power vs Time



Power vs Time
(Shot 160)
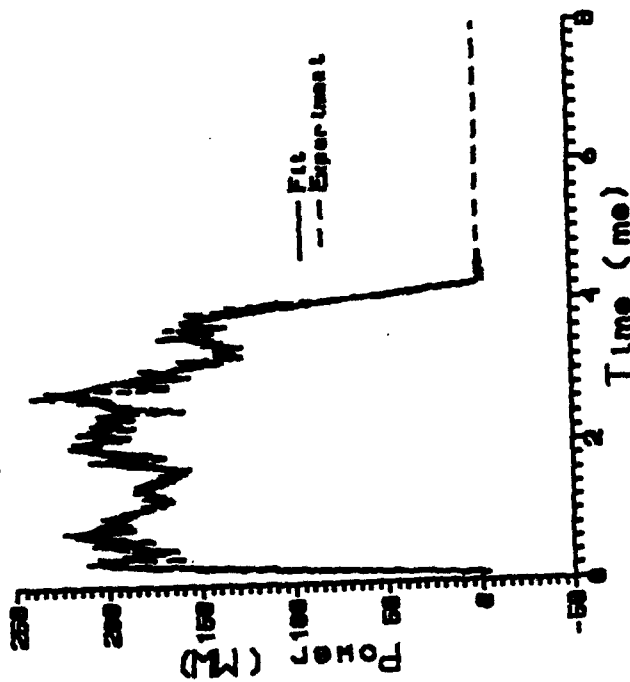
Power vs Time
(Shot 161)

239
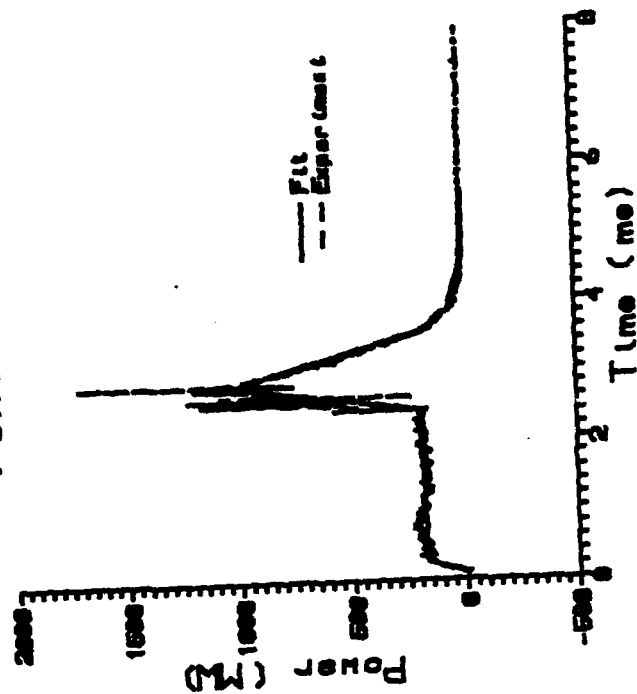
# Pressure vs Time



Breech Pressure vs Time
(Shot 161)

Breech Pressure vs Time
(Shot 160)
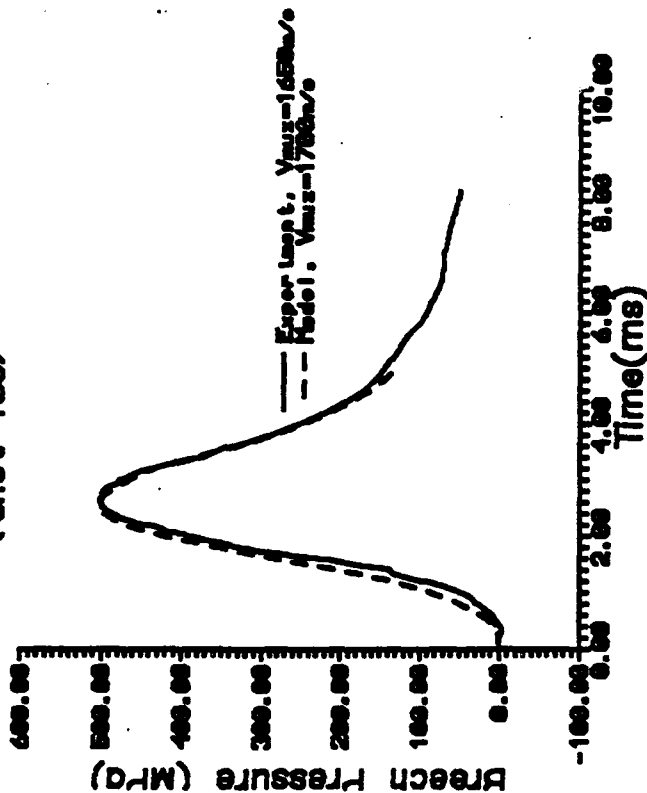
#1- Propellant burning rate (cm/s): r=.183796P$^{.830226}$
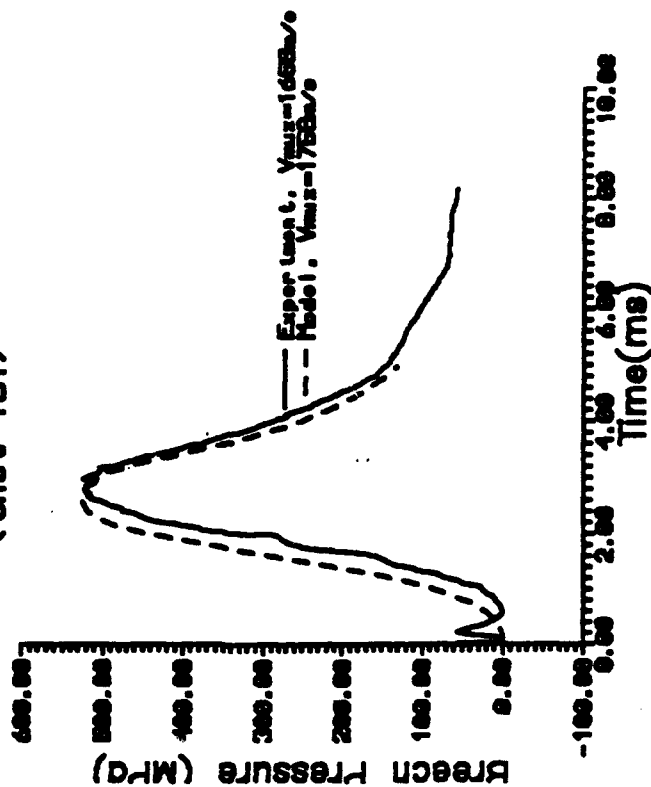
injection
time

influence
time
on p3

influence
time
on p4

THE PRESSURES IN SHOT 150 ARE
TIME SHIFTED (70 uSEC.)

r160-power

—— r160-p3
—— r160-p4
—— r160-p5
—— r160-p6
—— r160-p7

..... r161-p3
..... r161-p4
..... r161-p5
..... r161-p6
..... r161-p7
..... r161-power

340µs

340µs

5000.0
4000.0
3000.0
2000.0
1000.0
0.0

bar

241
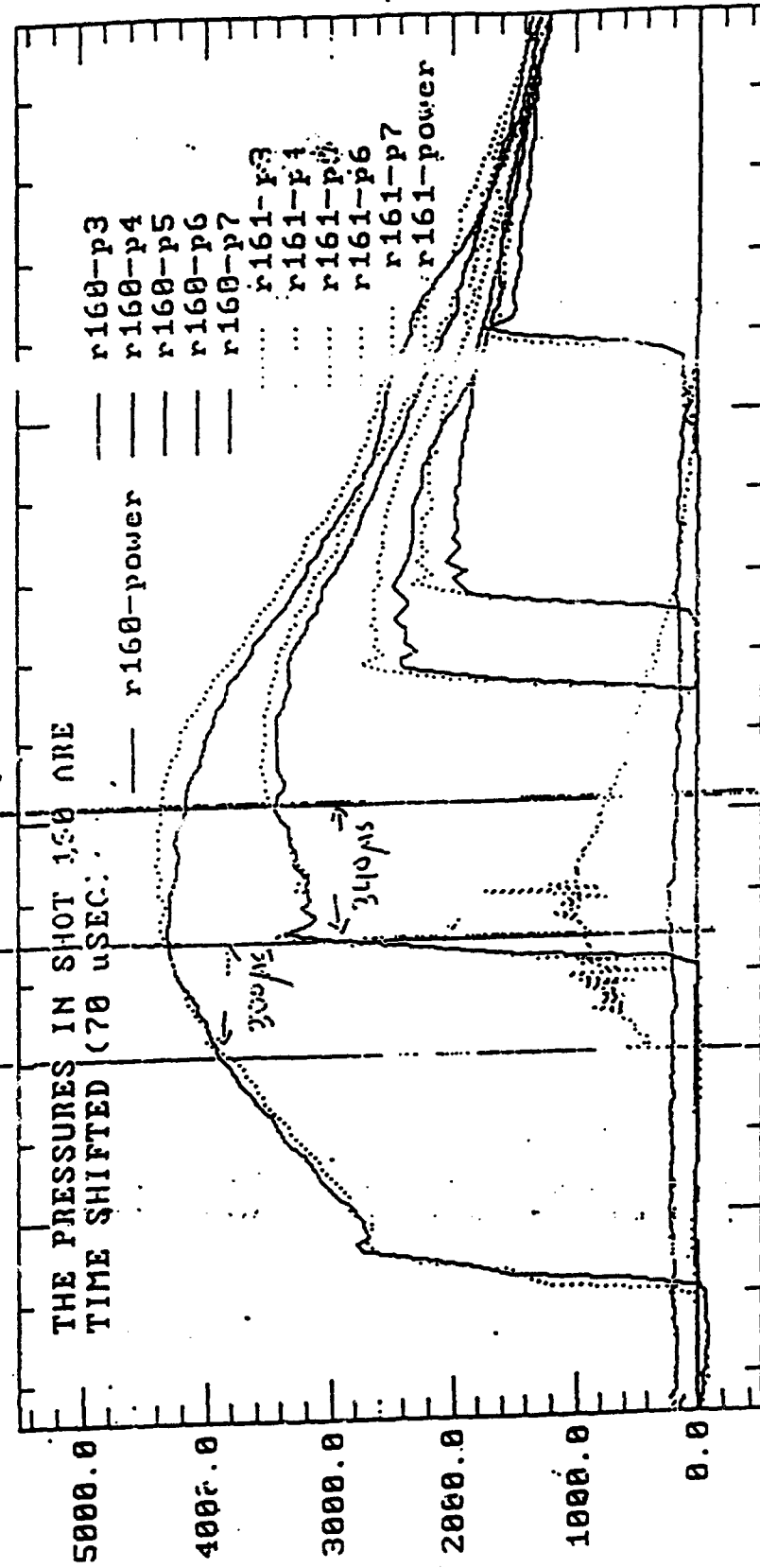
2.0ms          3.0ms          4.0ms
               TIME

#756   38.467 @ 1.512ms

$V_1 = 1692$ m/s

$V_2 = 1176$ m/s

$P3 \rightarrow x = 50.7cm$

$P4 \rightarrow x = 90.7cm$

Set 1

shot 160    mv = 1650 m/s
shot 161    mv = 1658 m/s

**ARL**

# Simulation of OCB14

- XNOVAKTC-ETC, 1D SP IB model (Gough)

  - uniform rupture of moderator tube at 0.3 ms
    based on pressure rise at combustion chamber gage
  - uniform ignition of propellant
  - plasma source term based on experiment
  - 100 microsecond delay in plasma energy

- Comparison

|  | Pmax | MV | Consumed mass |
|---|---|---|---|
| Experiment | 117 MPa | 570 m/s | 35.36 g (inverse) |
| Simulation | 131 MPa | 569 m/s | 33.93 g (XKTC) |

( initial charge: 65.3 g M43 propellant)

## Simulation of CCB14

Olin Shot 14, M43, Plasma Delay (0.1 ms)

Solid: Experiment, MV 672 m/s
Star : Simulation (March), MV 640 m/s

Breech Pressure (MPa)
Time (ms)
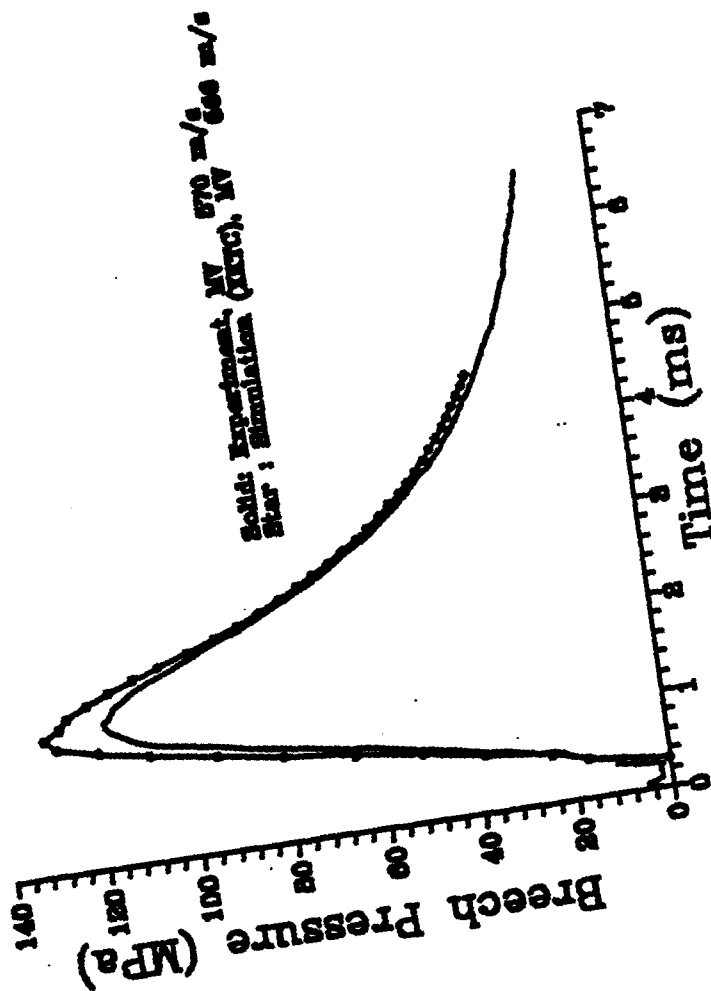
- **Unknowns**

  - M43 burn rate data at low pressure (< 20 MPa)
  - rupture of ullage tube & effect on bed rheology
  - effect of plasma on flamespreading
  - effect of plasma on ullage tube pressurization
  - response of projectile to ullage tube pressurization

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# Radial Structure of Temperature

**ARL**

**"LOG TEMPERATURE LEVELS AT 1.065 ms"**
**"SP ETC SHOT 45"**
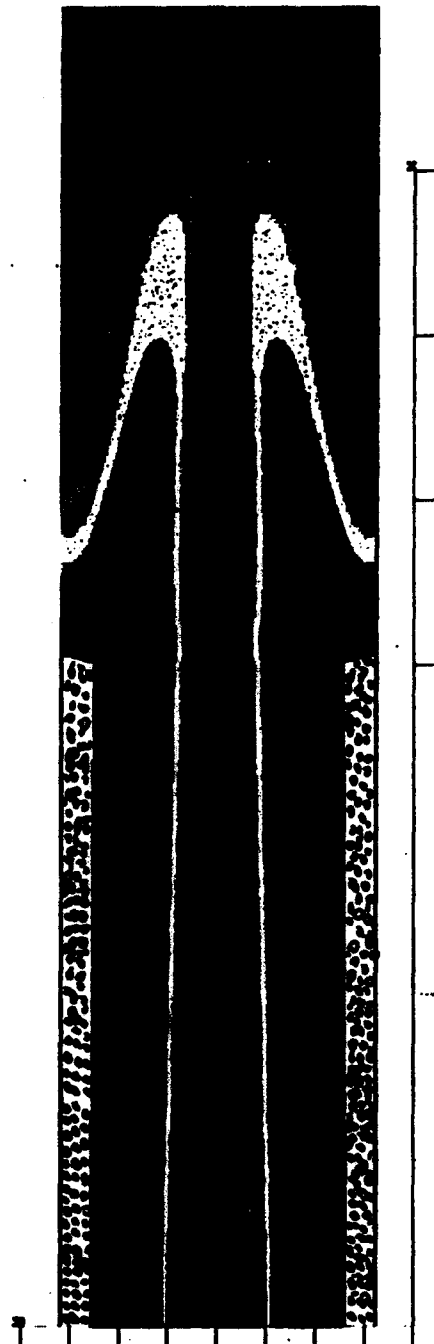
**"LOG TEMPERATURE LEVELS AT 1.465 ms"**
**"SP ETC SHOT 45"**

# Summary

**ARL**
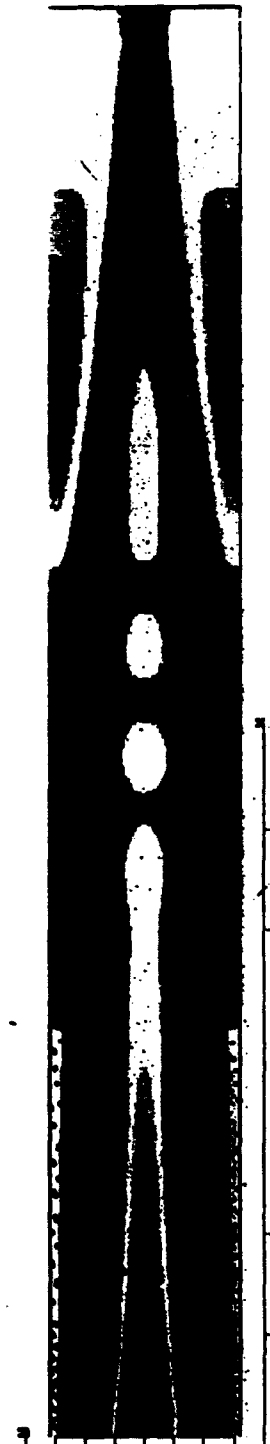
- **ETC gun models integral to research efforts**

- **Goal: predictive end-to-end models (appropriate dimensionality)**

  - dependent on physical process of interest
  - 0D, 1D, 2D, 3D models pertinent

- **Burn rate of solid propellant does not appear changed under influence of plasma at electrical energy densities investigated (<1.0 kJ/g)**

- **Status of IB models**

  - 0D models adequately capture macroscopic measurements & can be used for scoping studies

  - 1D models appear to be adequate if plasma components can be sufficiently modeled; useful for study of longitudinal phenomena such as pressure waves

  - 2D/3D models under active development; required to capture radial structure which is necessary for detailed cartridge design

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# ARL ETC MODELING WORKSHOP

# OLIN IRAD EFFORTS
# *RELATED TO ETC MODELING*

H. McElroy, K. Linde

12 - 13 MAY, 1993

**Olin**
ORDNANCE

# ACKNOWLEDGMENTS

Many Government, GT-Devices and other personnel have been of significant assistance in conducting the efforts described to date. We hope that the cooperative efforts outlined and planned for the future will also be supported as in the past.

In particular, G. Keller, P. Conroy, B. Oberle, G. Wren and N. Winsor contributed significantly to all phases and efforts.

# TOPICS

- Why Model - At Olin

- What we model now (routinely)

  - Equilibrium Thermochemistry

  - Simple Optimum Systems Upper Limit Bounds

  - Lumped Parameter or 0-D IB Models

- What we perceive as necessary for the future

- Challenges and Conclusions

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# WHY MODEL - AT OLIN

- Scoping new products/processes

- Quality Control

- Developing understanding of product capabilities & Limits

- Unraveling experimental data

- Preliminary safety & charge design

- Charge design verification studies

- Incident Analysis

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# WHAT WE MODEL ROUTINELY AT

## OLIN

- Equilibrium thermochemistry (Blake & MCVECP aka Hunter) with ET-C extensions

- CONPRESS - or constant chamber pressure model

*HUNT-CON - a combined equilibrium thermochem code with CONPRESS (hunter + conpress) and ET-C Extensions

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# LUMPED PARAMETER
# Ø-D IB Code - IBHVG2.504G6

- Propellant Form Function Extensions

  - Inside Burner Single Perf Outside Inhib Grain
  - 15 point deterrant function/layer model
  - 10 propellant bins
  - Cased telescoped system
  - Cigarette burn - attached to chamber

- ET-C Functionality - added by GT-Devices

- English to metric and vice versa input/output capability - added by D. Chiu ARDEC - Preserves extensive .400 series data bases.

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# LOADING GEOMETRY

OC26

30mm OLIN EXP DATA VS CODE RESULTS
OC 26–PCI

□ IBHVG2    —— EXP

THIS DOCUMENT CONTAINS OLIN CORPORATION COMPETITION–SENSITIVE MATERIAL

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254
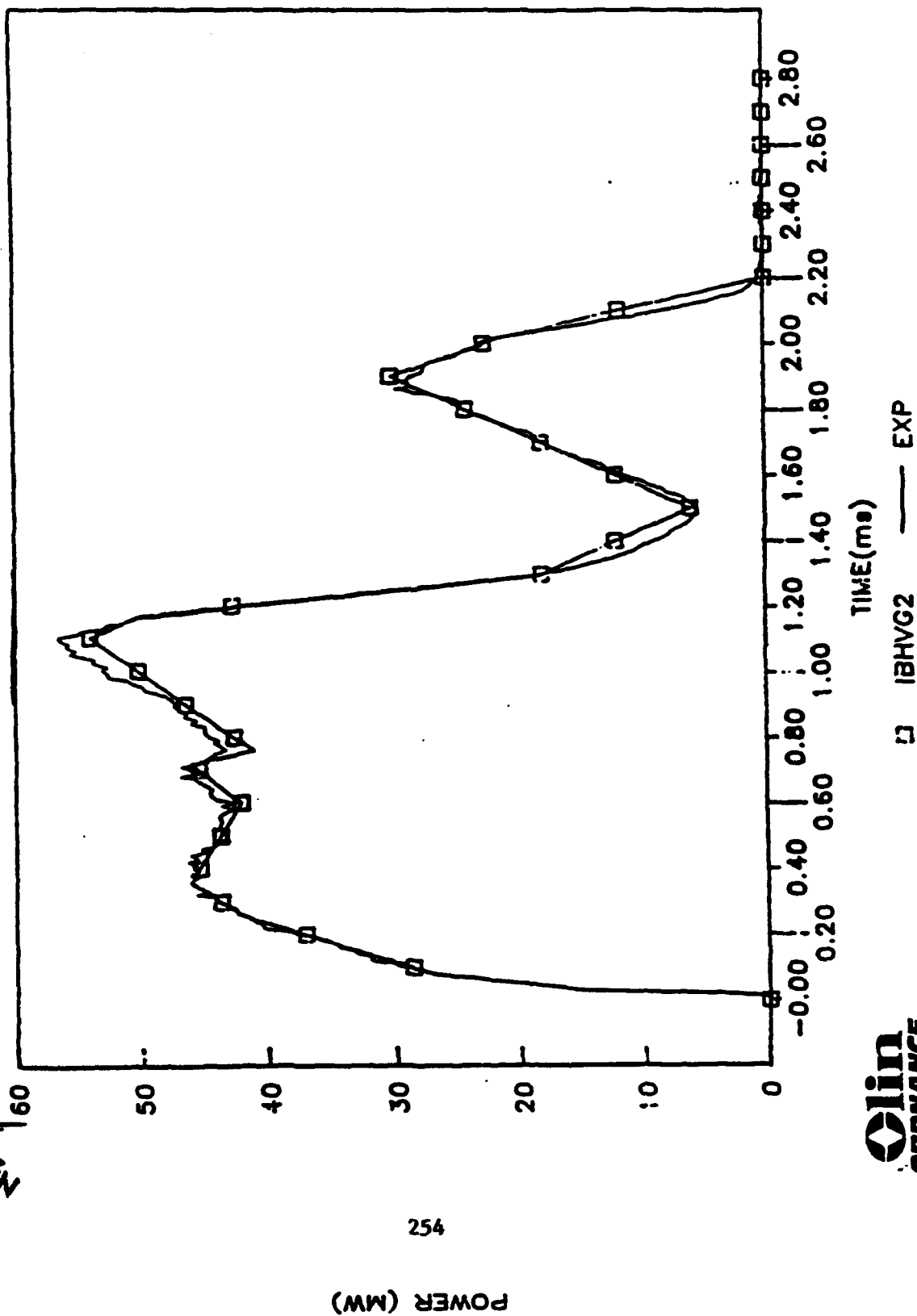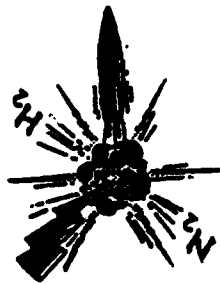
# 30mm OLIN EXP. DATA vs. CODE RESULTS
## OC26   PC1
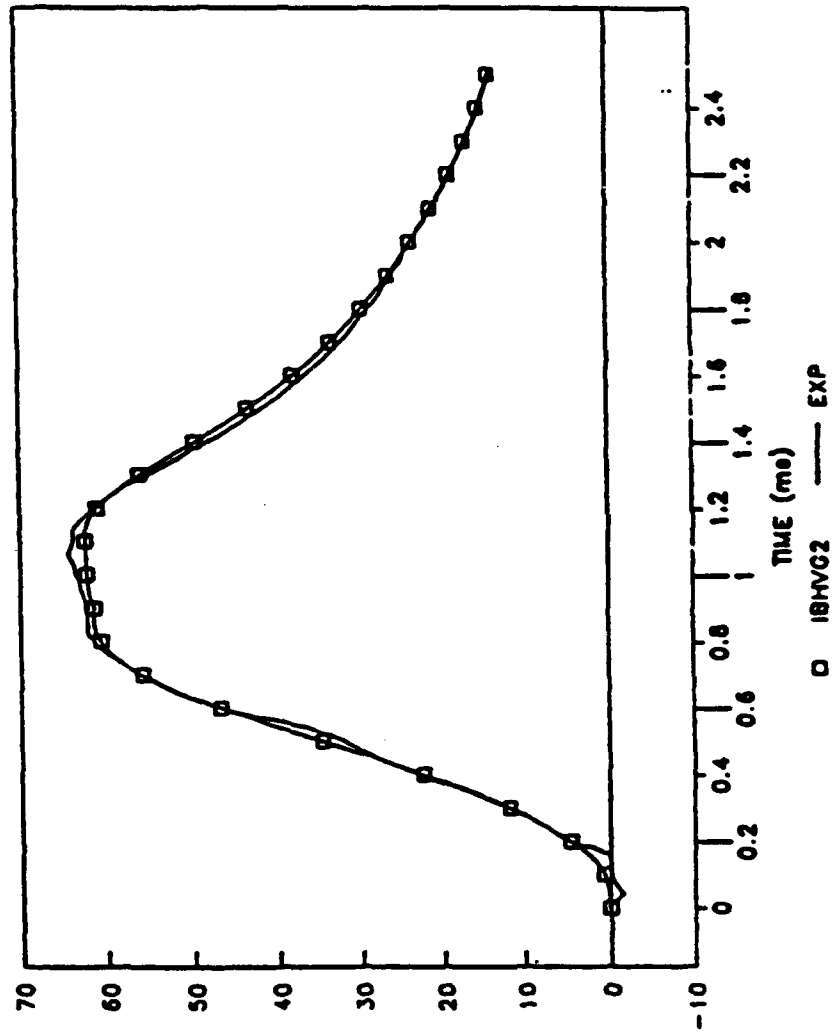


PRESSURE (kpaI)

TIME (ms)

□ IBHVG2    —— EXP

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CODE AND EXP. PROJECTILE TRAVEL
OC26

TIME (ms)

TRAVEL (cm)

——— IBHVG2     ◇ EXP

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# 1-D XNOVAKTC (modified)

## Beta Version
## 10426.+

- Modified input routines to accept extended IBHVG2.504 input decks - or old style card image input if you don't want to change.

- Added thoes extensions which we added to IBHVG2.504G6 which were not already in XNOVAKTC. (e.g. Pan Cake Function).

- Corrected minor chemistry bug in layer properties - they defaulted to all being the same and increased points to 15.

- Release to GT-Devices for input of ET-C functionality - End of May.

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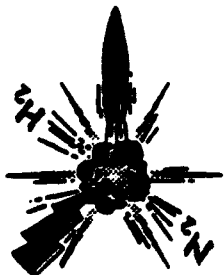
# SAMPLE DUAL INPUT DECK

## 30mm Subscale Artillery for Shot EF044

### Combined IBHVG2.504G6 & XNOVAKTC extensions

```
$COMM      This run converted to XNOVAKTC 3/19/93 HRL
        N0885.IN  !! Commented out at stuff.
        30mm SUBSCALE ARTILLERY REVERSE ENGINEERING FOR EF044
         USING ADJUSTED 4TH LAYER TRANSITION
        ADJUSTING RATIO OF LARGE TO SMALL GRAIN SIZES TO DEMONSTRATE
         PROCESS CONTROL
$INFO
        RUN = 30mm ARTILLERY RESULTS

$XCONTROL     $M2 CONTROL DATA
         NPRINT = 1    NGRAPH   = 0
         NDISK  = 0    DSKRD    = 0
         IBTABL = 1    NFLAM    = 1
         NPTABL = 1    NEROS    = 0
         NDYN   = 0    NHTW     = 1
         NBC = 0,0
                       $ NRES(1)= 0  NRES(2) = 0   $not used
         LDBED  = 1    $ 0 = PROP BED INITIALLY UNCOMPACT, 1=COMPACTED
         JHTW   = 0    $1
         LYER   = 0    $IBRES = 1 moved to resi
         NTC    = 0
                       $  INHIB = 0,0,0  NO LONGER NEEDED
         NXCW   = 0
         NBLOWN = 0
         NSWSOL = 0
         KMODE  = 0
         MODET  = 0    $ 1 = TANK GUN allows modeling of center hole in prop
         NECHO  = 0
         INBCX  = 0

$XINTEGRA    $M3 INTEGRATION PARAMETERS
         NDIM    = 15 $40  $20 $ 10 $20
         DTPRT   = 0
         NSTEP   =    100    TSTOP  = 0.02   $0.0002   $.0200
         NDTST   =     0     ZSTOP  = 60.184
         NSTOP   =   3500    TINT   = 0.0002
         NUNIN   =     0     SAFE   = 1.1   $3     $1.1
         NUNOUT  =     0     CRIT   = 0.2
                            RZOLV  = 0.05   $0.1    $0.05
                            TABLIB = 0.0002
                            TABLP  = 0.0001

$XFILECNT    $M4 FILE COUNTERS
        $ NSTA   = 4     moved to GUN $NUMBER OF TUBE DIAMETER STATIONS
         NTEM   = 0     NEL     = 0
         NEPS   = 0,0,0
        $ NZPT   = 3 $ MOVED TO RESI DECK
         MORE   = 0,0,0
         NBL    = 0


$GUN
      NAME    = '30MM SMOOTHBORE'    $        CHAM    = 10.0384
         $ GRVE    =   1.1811              LAND    =   1.1811
         $ G/L     =   1.0000              TWST    =   99999.9
         $ TRAV    =  53.7008             CLEN    =   7.8740
      NGAG    = 5   GLOC     = -8.8929, -2.0079, 2.4016, 25.2362, 51.4173
      NSTA = 4    $NUM of Stations in tube profile
      ZA =   0.0,  -7.55,   6.05,   60.184
      GUNDIA =1.26,  1.26,  1.1811,  1.1811     $ or use RA (radius)
      TWST = 99999 $ RIF = 6.0 or use TWST (TWST=360/RIF) Is this right????


   $RESI   $C12 BORE RESISTANCE - ERZ = DIST, BR = PRESSURE
```

IBRES = 1  $LINEAR RESISTANCE , 2=BASED ON VELOCITY
$ if TRAV or BRZ start with 0.0.the rest of the values are relative
$ to initial proj. location. if > 0.0 all is relative to breech

```
    $ AIR      = 1
      NPTS     = 4
      TRAV     = 0.0,  0.5169,  0.6169, 53.7008
      PRES     = 0.0,  1200.0,  100.00, 50.0018
```

$PROJ        $M13 PROJECTILE AND RIFLING CHARACTERISTICS
```
        ZBPR  = 8.05 $7.85  $8.05  $9.856
        PRWT  = 0.735 $ WTPR or PRWT or WT
        PRIN  = 0.14 $=POLAR MOM OF INERTIA --LBM-IN**2
          $RIF= 6.0 moved to $GUN
```

$XAMBGAS     $M5 AMB GAS PROPS
```
         TEMST = 530        PST      = 14.7
         GMST  = 29         GAMST    = 1.4
```

$XPROPBED    $M6 PROPELLANT BED GENERAL PROPS
```
         $ can use either: TEMPR ,or TEMPF, or, TEMPC
         TEMPC = 21.0
```

$PRIM        $C8 IGNITER THERMOCHEMISTRY
```
        NAME    = 'LX CAPILLARY'          $ CHWT     = .22046E-03
        GAMA    =   1.1100                COV      =  22.9743
        TEMP    =   300.00                FORC     =   33455.3
        $ EIG   = 6303000. or if FORC is used it will be used internally
        $        to calculate  EIG = (FORC*12.D0).(GAMA-1.D0)
        GMIG    = 36.13
      $ NOTE: Following is a guess and may not match IBHVG
        JJ = 3 $NUMBER OF TIMES
        II = 3 $NUMBER OF POSITIONS (SEE M4)
        POSIIG =   0.0,      2.0,     4.00
        TIMEIG = 0.006,    0.008,    0.010
        RATEIG =  0.070,   0.070,   0.070,
                  0.040,   0.040,   0.040,
                  0.010,   0.010,   0.010    $ no comments above this allow
```

$PROP
```
        NAME    = 'LX CAPILLARY'          GRAN     = 'IPF  $2  $'IPF'
        CHWT    =   0.0231               LEN      =  3.0000
        DIAM    =   0.5116               DP       =  0.1875
        $ WEB   =   0.1621
        GAMA    =   1.1100
        COV     =  22.9743              RHO      =  0.0434
        TEMP    =   300.00             FORC     =  33455.3
        ALPH    = 0.0                   BETA     =  55.1181
        $ NTBL = 1
      $ Note: nova input needs follow for prop det
        ZGRLFT   = 0.0   $LEFT HAND LOC OF BAG OF PROP I
        ZGRRHT   = 3.0   $ is this right ??
        RGRI     = 0.09375 $INNER RAD OF PROP      note this is one dimensional
        RGRO     = 0.2558 $OUTER RADIUS note: NOT used in code

        SLW   = 0.0   $SLOT WIDTH
        NFIX = 0   $ 0=GRAIN FREE TO MOVE, 1 = ATTACH TO   B, 2= ATT PROJ
        BONDX = 0.0   $ STRENGTH OF BOND

        GAP   = 17400.   $RHEOLOGY RATE OF PROPAGA OF STRESS OF SETTLED BED
        GEPO =0.8  $0.35   $ 0.820.28 $0.25 $0.301   $0.58387
        GCAP = 50000.   $RATE OF PROPAGA
        ANU   = 0         $POISSONS RATIO OF PROP
```

```
TEMPIG   = 810.    $ IGNITION TEMPERATURE
KP       = .0277   $ THERMAL CONDUCTIVITY
ALPHAP = .0001345  $ THERMAL DIFFUSIVITY
EMMIS    = .6      $ EMMISIVITY FACTOR


$PROP
   NAME      = 'LX MOD TUBE'
   CHWT      = 0.003307
   LEN       =  7.2441
   GRAN      = 'IPF'  $ 2 $ 'IPF'
   DIAM      =  0.19625            DPERF    =    0.1875
$  WEB       = 0.008736
   GAMA      =  1.1100
   COV       = 22.9743            RHO       =    0.0434
   TEMP      = 300.00            FORC      =   33455.3
   ALPHA     = 0.0              BETA       =   0.1969
   NTBL = 1
$ Note: nova input needs follow for prop dek
       ZGRLFT   = 0.0   $LEFT HAND LOC OF BAG OF PROP I
       ZGRRHT   = 7.24413  $RIGHT HAN BOUND
       RGRI    = 0.1875 $INNER RAD OF PROP      note this is one dimensional
       RGRO    = 0.19625 $OUTER RADIUS note: NOT used in code

       SLW  = 0.0  $SLOT WIDTH
       NFIX = 0   $ 0=GRAIN FREE TO MOVE. 1 = ATTACH TO TUBE. 2= ATT PROJ
       BONDX  = 0.0   $ STRENGTH OF BOND

       GAP  = 17400.  $RHEOLOGY RATE OF PROPAGA OF STRESS OF SETTLED BED
       GEPO =0.8  $0.35 .  $ 0.820.28 $0.25 $0.301   $0.58387
       GCAP = 50000.   $RATE OF PROPAGA
       ANU  = 0          $POISSONS RATIO OF PROP

       B1     = 0.0   $ BURN RATE CONSTANT
       TEMPIG   = 810.   $ IGNITION TEMPERATURE
       KP       = .0277  $ THERMAL CONDUCTIVITY
       ALPHAP = .0001345 $ THERMAL DIFFUSIVITY
       EMMIS    = .6     $ EMMISIVITY FACTOR

$PROP
   NAME      = 'WC885'                GRAN    = 'BALL  $18
$  IGNC   = 1                         THRC    = .50000E-03
   NTBL    = 1 $-1
   DIAM    =  0.0630
$  DL/S    = 0.008570,  0.0315,  0.0851  ! NOVA does not like /'s
   DLS     = 0.008570,  0.0315,  0.0851
$   DEPL  = 0.0005399, 0.0019845, .0053613
   RHOL    =   0.0539,  0.0539,  0.0548,  0.0589
   GAML    =   1.2850,  1.2850,  1.2790,  1.2340
   FRCL    =  254259.7, 254259.9, 278213.9, 373962.8
   COVL    =  30.8077, 30.8077, 30.9184, 26.4897
   TMPL    =    1896.7,  1896.9,  2109.4,   3471.2
   COEL  = .62236E-03, .62236E-03, .75113E-3, 0.001788
   EXPL  =  0.8053,   .8053,     .8053,     .8053
   CHWT    =   0.3336
$ Note: nova input needs follow for prop dek
       ZGRLFT   = 0.0   $LEFT HAND LOC OF BAG OF PROP I
       ZGRRHT   = 7.5  $guess  $RIGHT HAN BOUND
       RGRI    = 0.25 $guess$INNER RAD OF PROP  note this is one dimensional
       RGRO    = 0.63 $OUTER RADIUS note: NOT used in code

       SLW  = 0.0   $SLOT WIDTH
       NFIX = 0   $ 0=GRAIN FREE TO MOVE. 1 = ATTACH TO TUBE, 2= ATT PROJ
       BONDX  = 0.0   $ STRENGTH OF BOND

       GAP  = 17400.   $RHEOLOGY RATE OF PROPAGA OF STRESS OF SETTLED BED
```

```
JETO            $ 7.3   ...            $  ...
GCAP  = 30000    $RATE OF PROPAGA
ANU   = 0        $POISSONS RATIC OF PROF


BI        = 0.0      $ BUPN RATE CONSTANT
TEMPIG    = 810.     $ IGNITION TEMPERATURE
P         = .0277    $ THERMAL CONDUCTIVITY
ALPHAP    = .0001345 $ THERMAL DIFFUSIVITY
EMMIS     = .5       $ EMMISIVITY FACTOR


#COMM
    $ FOUR LAYER PROPELLANT MODEL (NOMINAL 1MM DIAM)
  $ warning this dek is metric because was comented out during convers
    NAME      = 'WC685'                    GRAN    = BALL
    IGNC = 1          THRC = 0.0002
    DIAM      = 0.00100838
    NTBL      = -1
    DL/S      = 0.0136, 0.0500, 0.1350
    RHOL      = 1492.6, 1492.6, 1515.8, 1631.3
    GAML      = 1.285, 1.285, 1.279, 1.234
    FRCL      = 760000, 760000, 831600, 1117800
    COVL      = 0.001113, 0.001113, 0.001117, 0.000957
    TMPL      = 1896.9, 1896.9, 2109.4, 3471.2
    CF1L      = 0.00087        EX1L      = 0.8053
    CF2L      = 0.00087        EX2L      = 0.8053
    CF3L      = 0.00105        EX3L      = 0.8053
    CF4L      = 0.00250        EX4L      = 0.8053
    CHWT      = 0.1513

  $ETC
    $ WARNING This is metric et dek*******************************
        PFAC=1
        NPWR = 9
    TPWR = 0, 3E-5, 6E-5, 1.2E-4, 1E-3, 1.25E-3, 1.52E-3, 1.7E-3, 2E-3
    PWR = 0, 0, 4.4E6, 2.4E6, 4.6E6, 1.85E6, 0.45E6, 0.09E6, 0
$END
```

WHAT WE PERCEIVE AS NECESSARY FOR
THE FUTURE • IRAD PLAN

CY 93 → BEYOND

OLIN IRAD FUNDS

COOPERATIVE PARTNER SHARE

COOPERATIVE EXPERIMENTS WITH:

| U.S. GOVT. | GT DEVICES |
|---|---|
| ARL / NAVY | GDLS |
| ARDEC | |
| SSDC / EGLIN AFB | |
| NAT LABS | |

PHYSICS

HIGH LD>1.3 g/cc
BED RHEOLOGY
BED POROSITY
BED COMPACTION
FLAME SPREAD ISSUES
PLASMA / MODERATOR INTERACTIONS
PLASMA / PROPELLANT INTERACTIONS
CHEMICAL KINETICS / PATH MODIFICATION STUDIES
VISUALIZATION STUDIES / X-RAY DIAGNOSTICS
GUN FIRINGS / DIAGNOSTICS / SHORT TUBE / LONG TUBE

(*U.S. GOVT. DEVELOPED)

CODE
0-D IB
1-D IB XKTC
1-1/2-D IB XKTC(M)
2D NG *
3D NG *

olin ORDNANCE

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WG 6493 13373

THIS DOCUMENT CONTAINS OLIN ... COMPETITION-SENSITIVE MATERIAL

# CHALLENGES FOR ETC MODELING

- Modeling technology must advance rapidly over next two years.

- Funds for 6.1/6.2 work appear scarce.

- For solids (ET-C) near to medium term technology (modeling) issues not as severe as liquids but significant technology challenges are present.

- Severe lack of high charge density/loading density experimental data with ET-C systems critical potential show stopper for modeling.

- US Government must articulate IM requirements more strongly as associated with ET-C.

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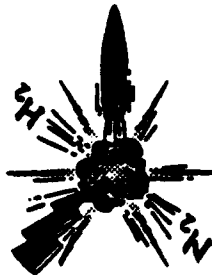
# CONCLUSIONS

- Modeling community must pull together - under **ARL** Guidance/Sponsorship/Leadership.

- Physics experiments must be jointly/cooperatively conducted to leverage scarce 6.1/6.2 resources all sources - Navy, Army, SDC, DNA, Air Force.

- We must be creative in our approaches.

- Olin will sell no propellant or cartridge systems before their time.

Our goal is to field ammunition/ctg systems. **NOT** Conduct long term R & D - Modeling is only one of the tools (but a necessary one)

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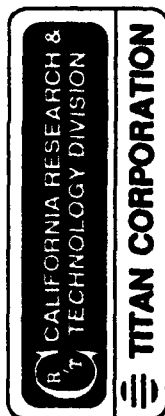
# Application of PDF Turbulent Combustion Model to

# Electrothermal-Chemical (ETC) Guns

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12 May 1993

# ETC Gun Modeling at CRT: Background

- Defense Nuclear Agency (DNA) sponsored ETC gun modeling under Turbulent Chemistry Modeling contract

- Work was performed over ~1 year period ending 12-92

- Contract emphasized turbulent mixing and combustion aspects of problem

# Unmixedness Modeling Using PDF Approach

## Problem Definition

- Suppose we have a computational cell containing reactants $\alpha$ and $\beta$ and product $\gamma$ which is generated in an irreversible reaction (the assumption of irreversibility is not required):

$$\alpha + \beta \rightarrow \gamma$$

- The mean mass fractions of $\alpha$ and $\beta$, $\overline{C_\alpha}$ and $\overline{C_\beta}$, are known

- The turbulent correlation $\overline{C'_\alpha C'_\beta}$ can be calculated from the second-order closure turbulence model (we have to model a source term in the evolution equation for this correlation, however)

- What is the rate of production of $\gamma$, i.e., $\overline{\dot{W}_\gamma}$?



computational cell

$$\dot{w}_\gamma = K\, C_\alpha\, C_\beta$$
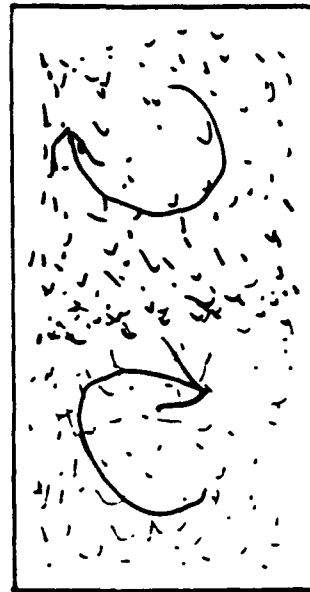
# Unmixedness Modeling Using PDF Approach (continued)

## Donaldson Unmixedness Approach

- Postulate the existence of $N$ states within the cell, where each state is characterized by $C_{\alpha,i}$ and $C_{\beta,i}$ (and, in general, temperature $T_i$), i.e., approximate a continuous pdf with a finite number of Dirac delta functions $\delta_i$ with strengths $\varepsilon_i$.
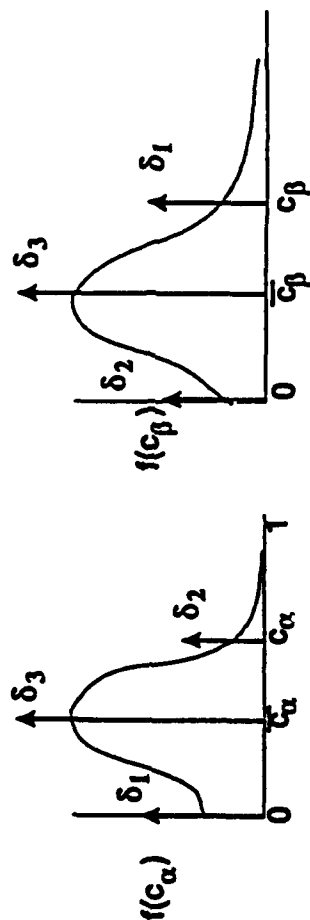


- Calculate the probability $\varepsilon_i$ of each state.

- Calculate the expectation of the rate of production of $\gamma$ from the known states and $\varepsilon_i$s:

$$\overline{\dot{W}_\gamma} = \sum_{i=1}^{N} \varepsilon_i \dot{W}_{\gamma,i}$$

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# Turbulent Unmixedness Modeling: Choice of States for a Two Species System

Suitable events should include states at the mean (i.e., when turbulence levels are low) as well as states where one or both concentrations disappear (intermittency).

If $\overline{c_1' c_2'} < 0$, we may choose

State 1: $c_{1,1} = 0$, $c_{2,1} = 2\overline{C_2}$

State 2: $c_{1,2} = 2\overline{c_1}$, $c_{2,2} = 0$

State 3: $c_{1,3} = \overline{c_1}$, $c_{2,3} = \overline{c_2}$

Or if $\overline{c_1' c_2'} > 0$,

State 1: $c_{1,1} = 0$, $c_{2,1} = 0$

State 2: $c_{1,2} = 2\overline{c_1}$, $c_{2,2} = 2\overline{c_2}$

State 3: $c_{1,3} = \overline{c_1}$, $c_{2,3} = \overline{c_2}$
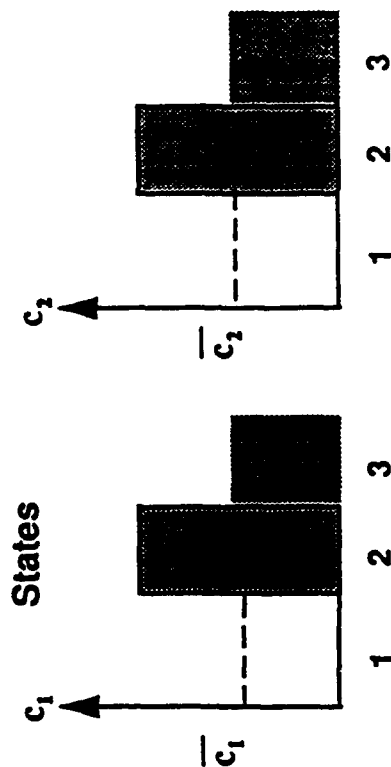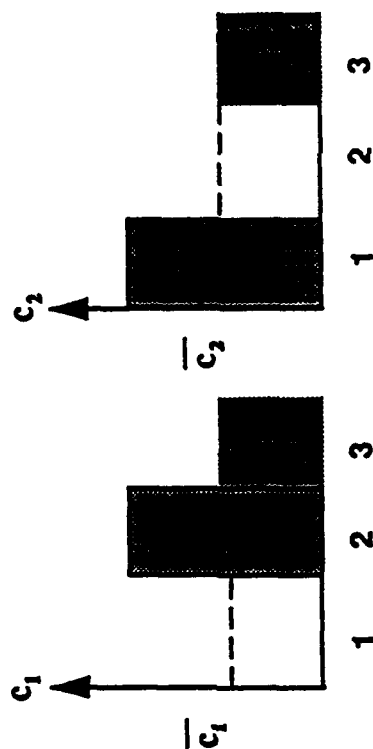
States

# Determination of PDF

## Constraints

$$\sum_{i=1}^{N} \epsilon_i \, c_{\alpha i} = \bar{c}_\alpha$$

$$\sum_{i=1}^{N} \epsilon_i \, c_{\beta i} = \bar{c}_\beta$$

$$\sum_{i=1}^{N} \epsilon_i \, c_{\alpha i} \, c_{\beta i} = \overline{c_\alpha c_\beta} = \bar{c}_\alpha \bar{c}_\beta + c'_\alpha c'_\beta$$

$$\sum_{i=1}^{N} \epsilon_i = 1$$

If number of states exceeds number of constraints, we need an additional criterion.

## Maximize Entropy by minimizing

$$\sum_{i=1}^{N} \epsilon_i \, \ln(\epsilon_i)$$

$\mathcal{C}_{\mathbf{R}_{T}}$

# Solution Procedure for Probabilities

## Lagrange multiplier method

Define F =

$$\sum_{i=1}^{N} \varepsilon_i \ln \varepsilon_i \; + \; \lambda_{01}\left(\sum_{i=1}^{N} \varepsilon_i C_{\alpha,i} - \overline{C_{\alpha}}\right) \; + \; \lambda_{02}\left(\sum_{i=1}^{N} \varepsilon_i C_{\beta,i} - \overline{C_{\beta}}\right) \; + \; \lambda_{12}\left(\sum_{i=1}^{N} \varepsilon_i C_{\alpha,i} C_{\beta,i} - \overline{C_{\alpha} C_{\beta}}\right)$$

$$+ \lambda_{00}\left(\sum_{i=1}^{N} \varepsilon_i - 1\right).$$

Then:

$$\varepsilon_i = \exp\left(-1 - \lambda_{01} C_{\alpha,i} - \lambda_{02} C_{\beta,i} - \lambda_{12} C_{\alpha,i} C_{\beta,i} - \lambda_{00}\right).$$

Solve for Lagrange multipliers using Newton's method, e.g.

# Temperature Spotiness Modeling

## Approach

- Determine the temperatures $T_i$ associated with each state $i$ (whose probabilities have already been calculated) by minimizing the function:

$$\sum_{i=1}^{N} \varepsilon_i T_i^2$$

subject to the constraints:

$$\sum_{i=1}^{N} \varepsilon_i C_{\alpha,i} T_i = \overline{C_\alpha T} \quad \text{and} \quad \sum_{i=1}^{N} \varepsilon_i C_{\beta,i} T_i = \overline{C_\beta T} .$$

i.e., maximize the entropy of mixing. Again, using Lagrange multipliers, solve for $T_i$

$$T_i = \lambda_1 C_{\alpha,i} + \lambda_2 C_{\beta,i}$$

# Temperature Spottiness Modeling (continued)

- We must also satisfy a constraint on $\overline{T^2}$, however, and therefore an additional degree of freedom is needed (consider the case of only 1 species when there could be no unmixedness, but still there are temperature fluctuations). Introduce an additional parameter $\delta$ such that:

$$\varepsilon_{i1} = \varepsilon_i(1+\delta)/2, \quad \varepsilon_{i2} = \varepsilon_i(1-\delta)/2,$$
$$T_{i1} = T_i/(1+\delta), \quad T_{i2} = T_i/(1-\delta).$$

The constraint then becomes:

$$\overline{T^2} = \sum_{i=1}^{N}\left(\varepsilon_{i1}T_{i1}^2 + \varepsilon_{i2}T_{i2}^2\right),$$

and delta is:

$$\delta = \sqrt{1 - \frac{1}{\overline{T^2}}\sum_{i=1}^{N}\varepsilon_i T_i^2}.$$

# ETC Gun Modeling Approach

- ## Model from "first-principles":

  – Fluid dynamics of plasma, liquid and vaporized working fluid components, reaction products

- ## Use detailed parameterizations for:

  – Mass, momentum, and heat transfer between gas and liquid (droplet) phases

  – Turbulence

  – Turbulent mixing and reaction of chemical species

  – Entrainment of droplets from working fluid

# ETC Gun Modeling Approach (continued)

- **Model simply:**

  - Addition of electrical energy to plasma

  - Chemical kinetics

  - Projectile motion

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# ETC Gun Modeling Approach Schematic

**Working Fluid**
Fuel:   n-octane
Oxidizer:  hydrogen peroxide

Right boundary moves based on analytical expression for projectile motion.

line of symmetry

Plasma Tube

**Computational Cell**
- sub-grid model for cell with liquid and gas is used
- multiphase equation of state is used

sub-grid parameterization models droplet entrainment as a function of turbulent stresses and liquid surface tension

**Fluid Species**
- fuel+oxidizer liquid
- fuel vapor
- oxidizer vapor
- products vapor
- plasma

**"Particle" Species**
- fuel+oxidizer droplets

CRT0493-01PM

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# ETC Gun Calculation Description

## Features

- Simulation of DNA Shot #7

- 30mm nominal diameter, 57.4 caliber, projectile weight = 339 g

- Gun chamber is scaled version of 155mm gun chamber

- Propellant is 85% $H_2O_2$ by volume, 15% RJ4 (simulated by octane), 166 cc

- Total electrical energy input = 168 KJ, added over 1.1 msec

- 2-D MAZe code (axisymmetric)

plasma injector  combustion chamber  projectile

radius (mm)

Distance (mm)

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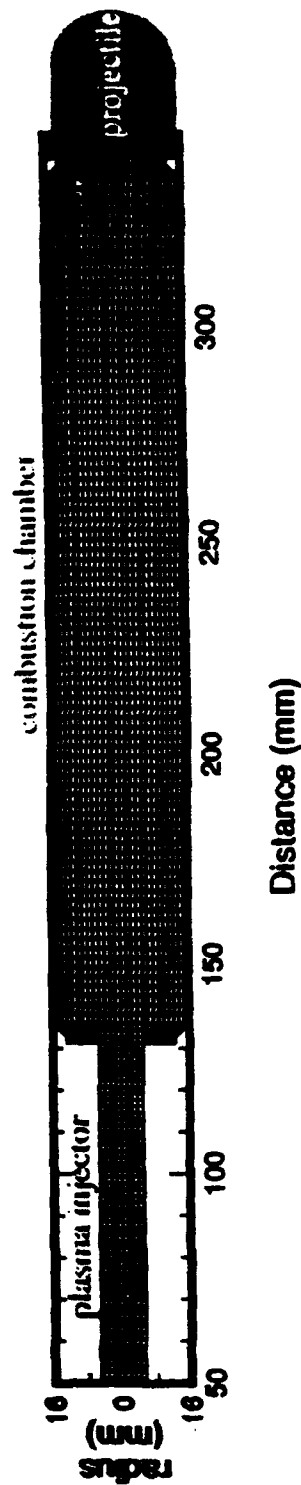
MAZe Code Simulation of 30mm ETC Gun Test
Selected Densities at 0.50 msec
Turbulent Unmixedness Case

Total Droplet Density

Oxidizer Vapor Density

Fuel Vapor Density

Product Density

Distance (mm)

$\log_{10}(\rho)$
$\log_{10}(g/cc)$

0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
-1.40
-1.60
-1.80
-2.00
-2.20
-2.40
-2.60
-2.80
-3.00
-3.20
-3.40
-3.60
-3.80
-4.00
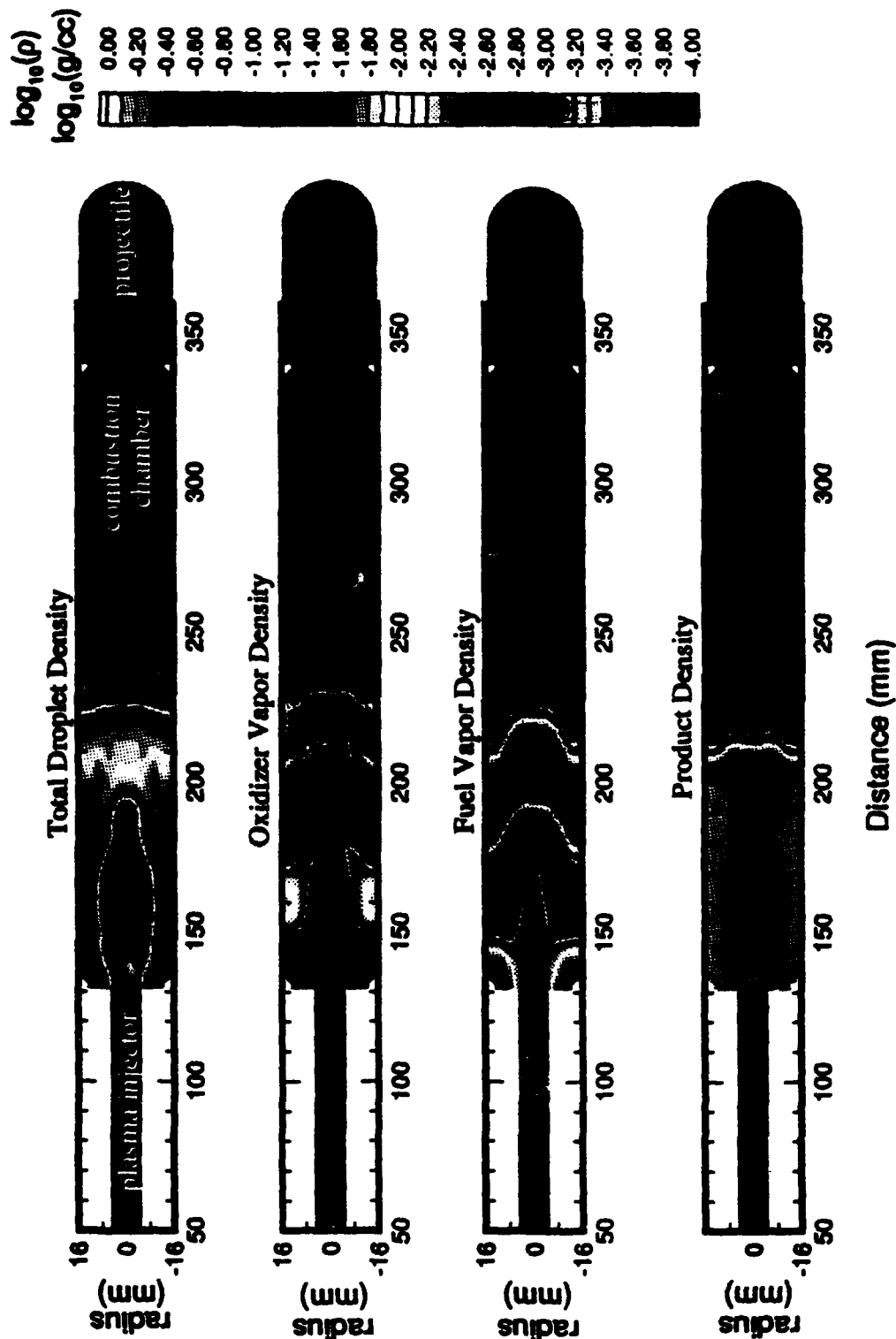
MAZe Code Simulation of 30mm ETC Gun Test
Droplet Density  Time = 0.50 msec
Turbulent Unmixedness Case

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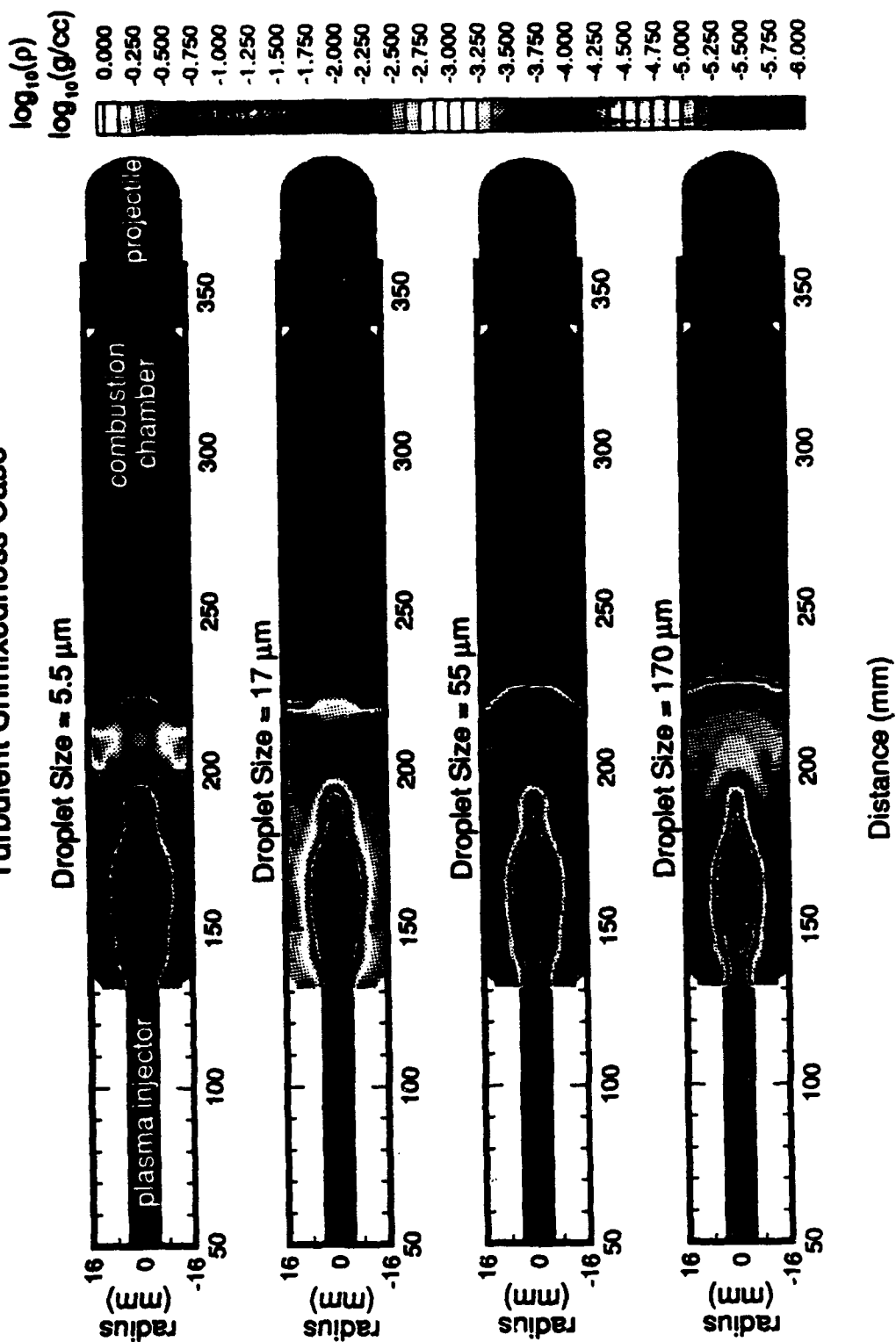
MAZe Code Simulation of 30mm ETC Gun Test
Droplet Extinction Time   Time = 0.50 msec
Turbulent Unmixedness Case
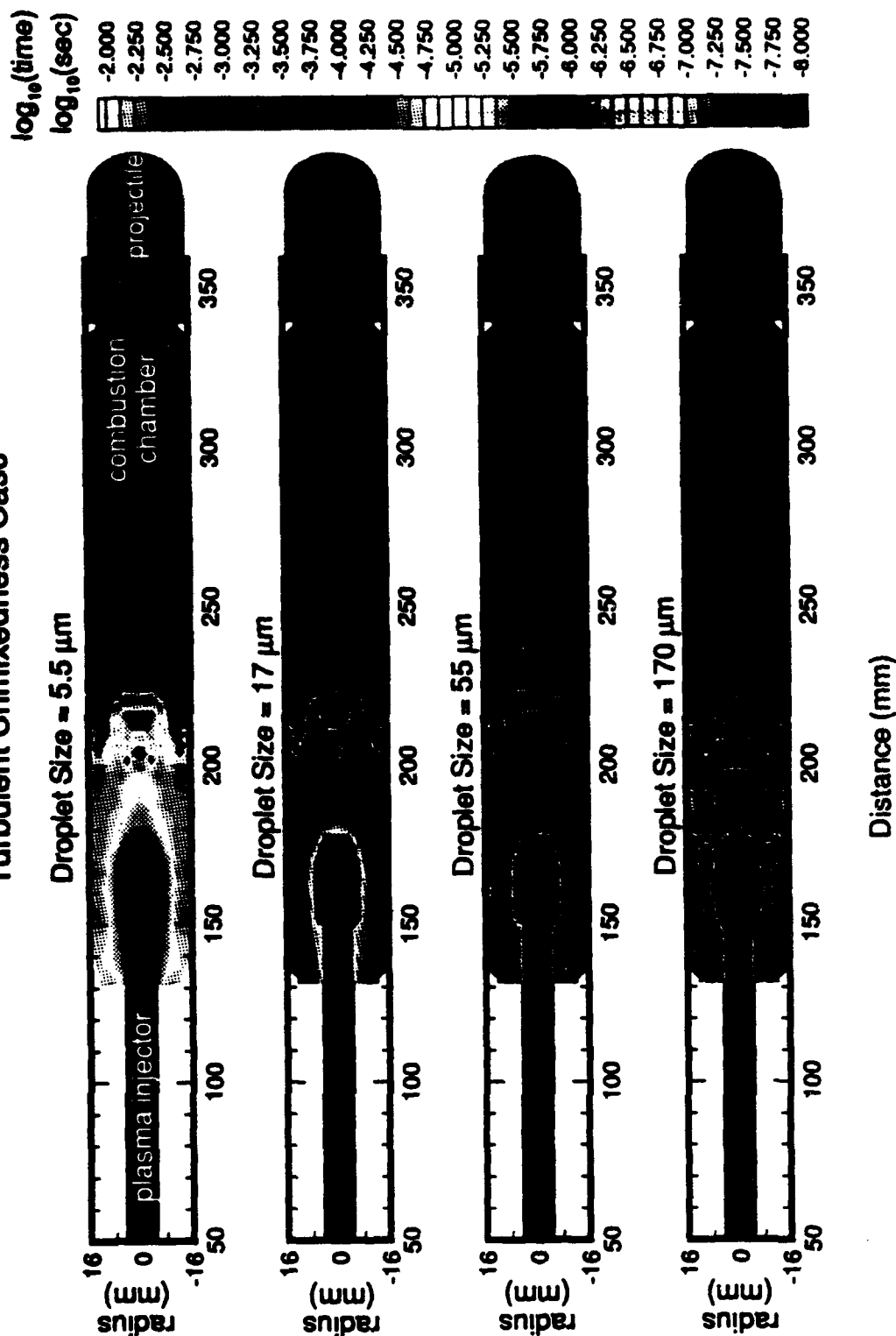
MAZe Code Simulation of 30mm ETC Gun Test
Turbulent Damköhler Number ($t_{mix}/t_{evap}$)  Time = 0.50 msec
Turbulent Unmixedness Case
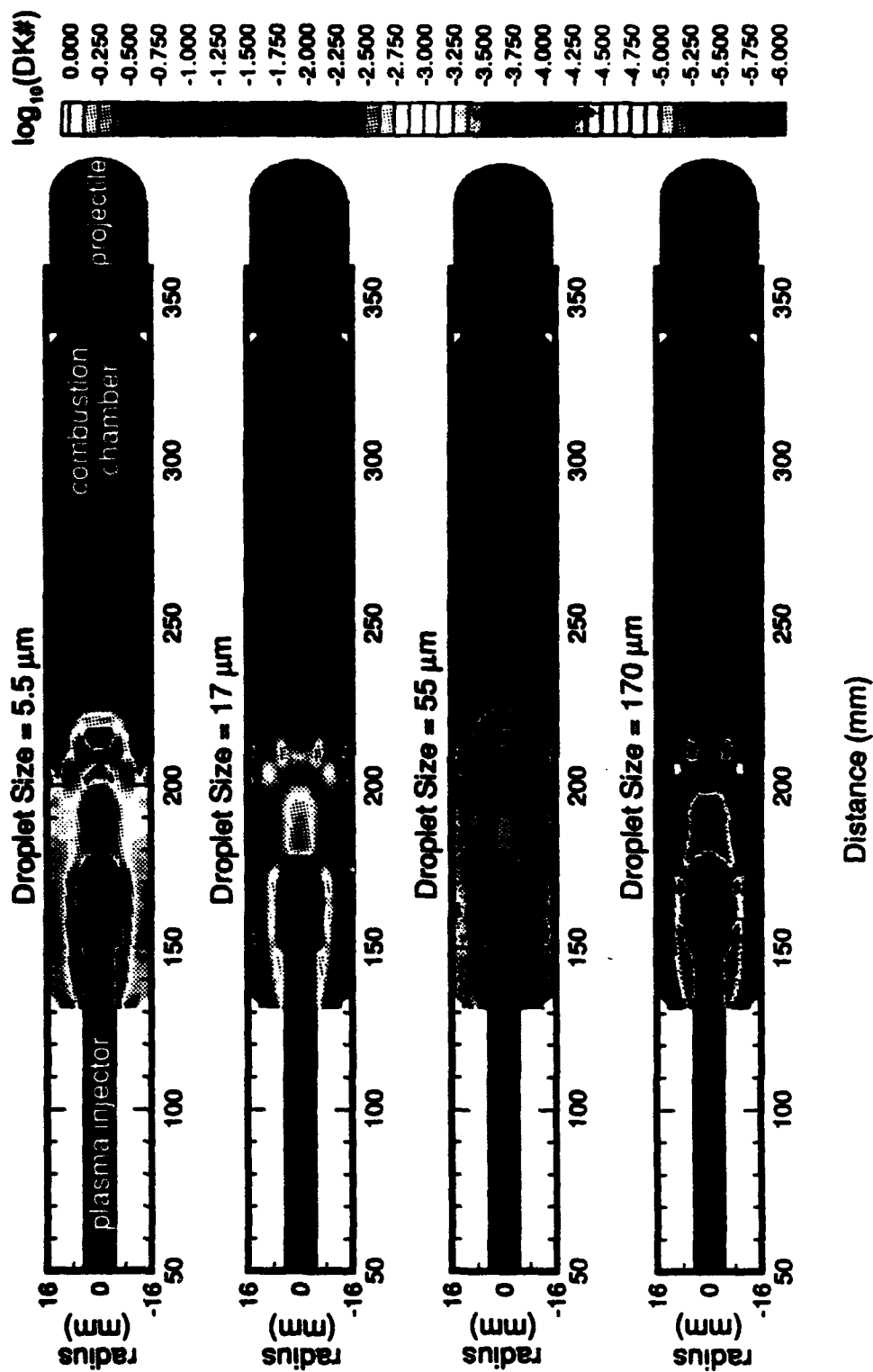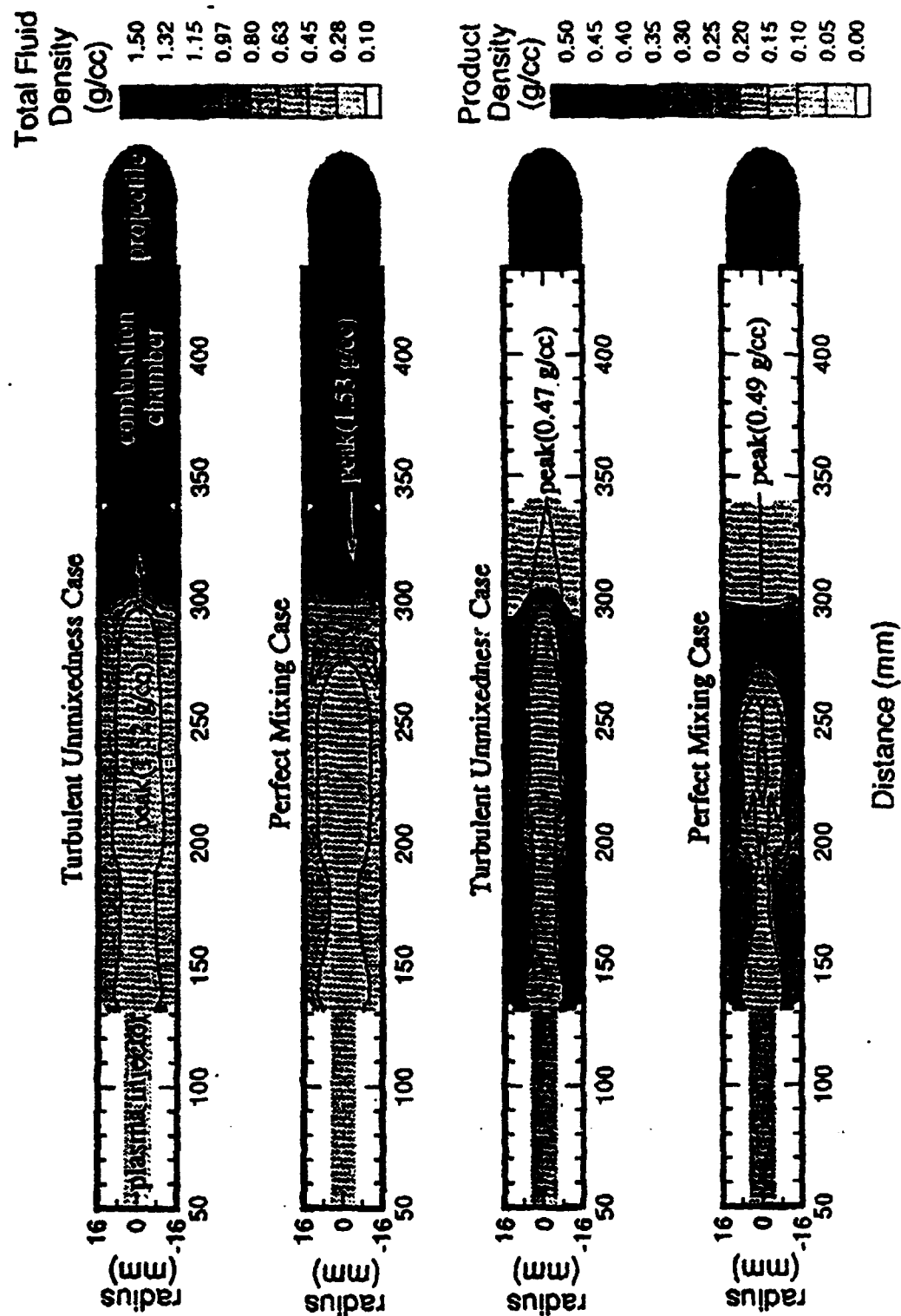
Figure 17. Comparison of turbulent unmixedness and perfect mixing cases at 1.1 msec: total fluid density and product density contours.
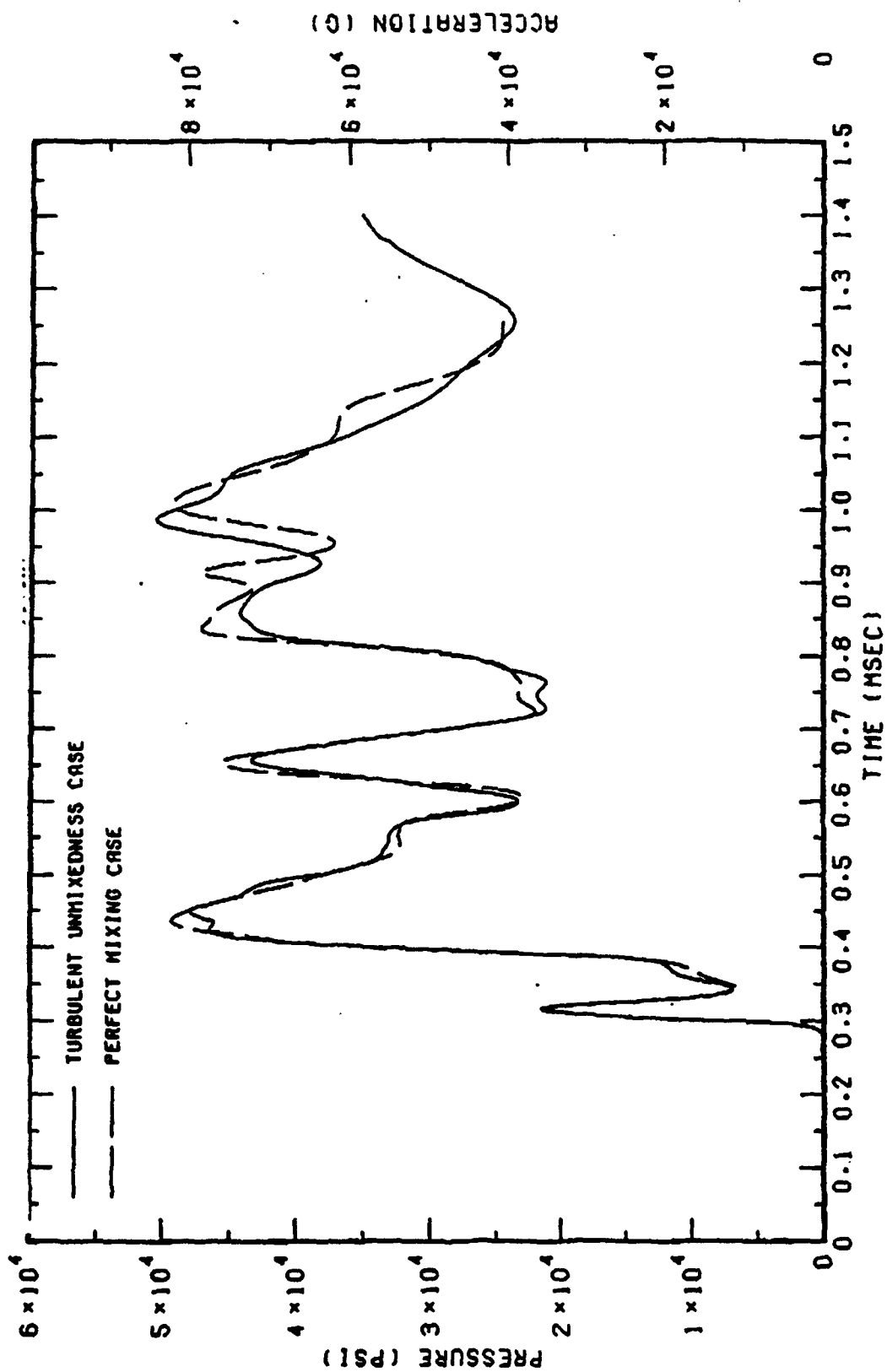
Figure 6. Projectile base pressure and acceleration time history.

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MAZe Code Simulation of 30mm ETC Gun Test
Comparison with Experimental Overpressure Time-Histories

— MAZe Calculation, X = 164 mm
— Experimental Data, X = 164 mm

MAZe Code Simulation of 30mm ETC Gun Test
Comparison with Experimental Overpressure Time-Histories

MAZe Calculation, X = 305 mm
Experimental Data, X = 305 mm

Time (msec)
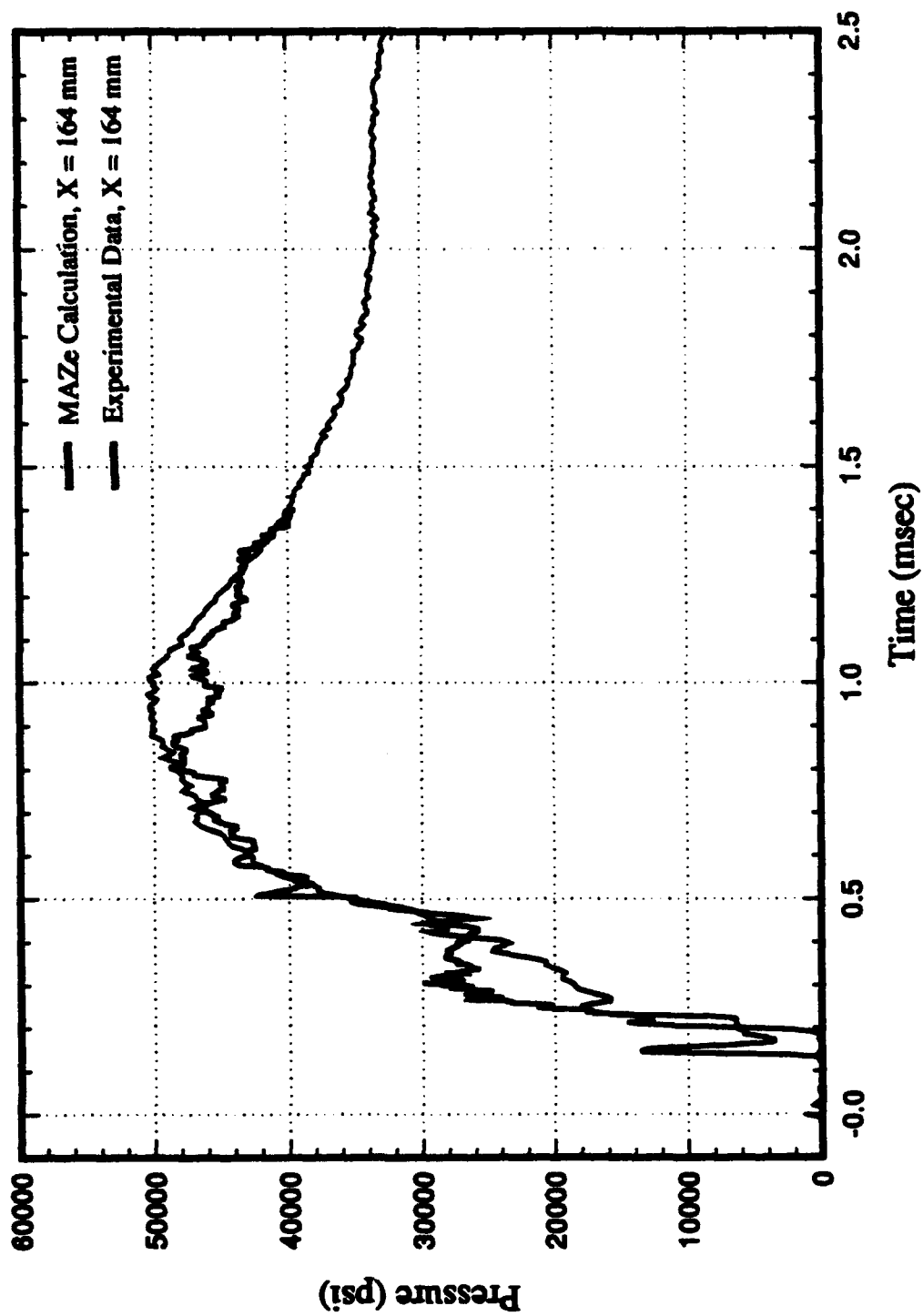
Pressure (psi)
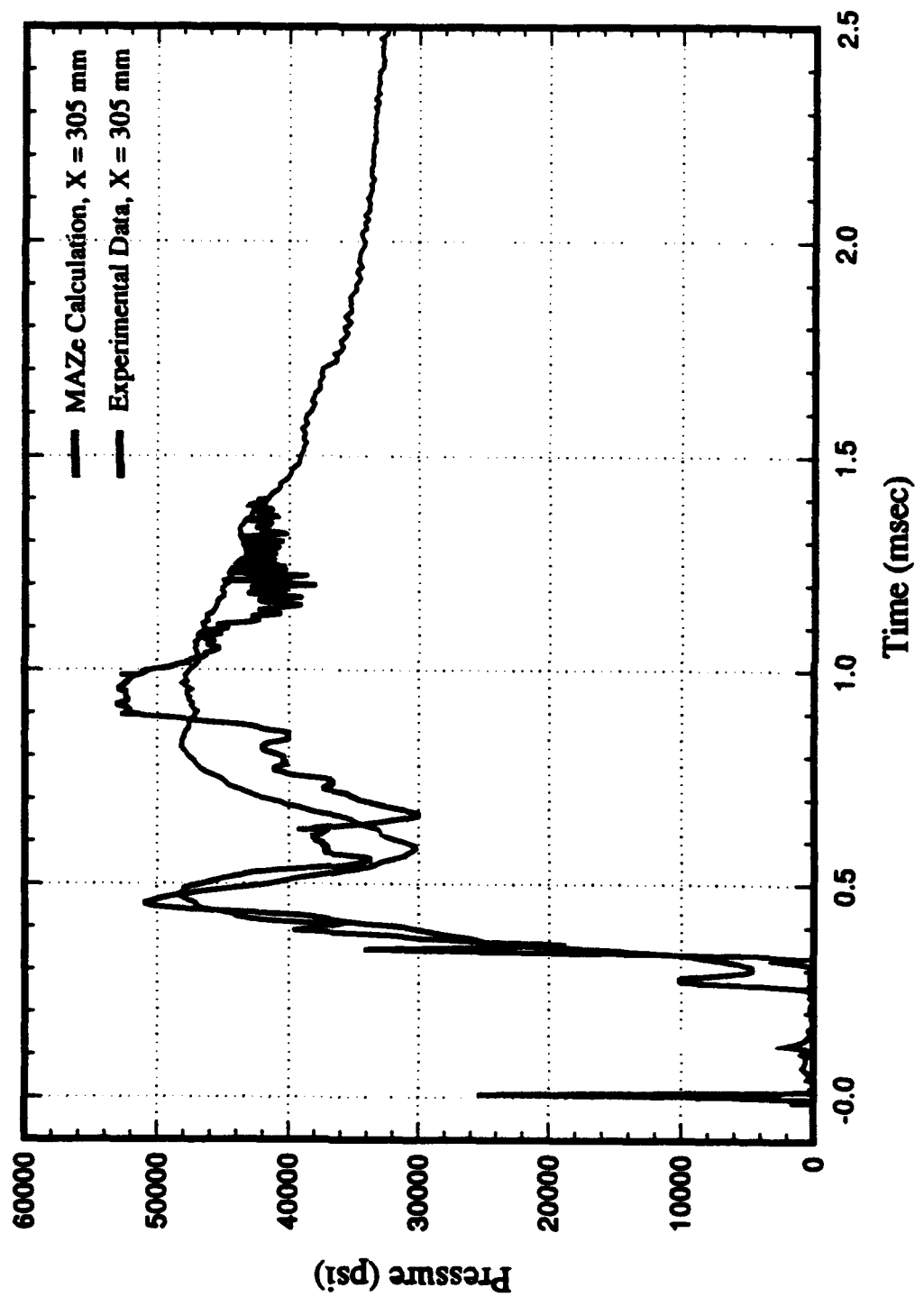
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